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U. S. DEPARTMENT OF AGRICULTURE.

BUREAU OF PLANT INDUSTRY—BULLETIN NO. 230.

B. T. GALLOWAY, *Chief of Bureau.*

THE WILTING COEFFICIENT FOR DIFFERENT PLANTS AND ITS INDIRECT DETERMINATION.

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Issued February 3, 1912.

WASHINGTON:
GOVERNMENT PRINTING OFFICE,
1912.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Plant Industry,
Office of the Chief,
Washington, D. C., August 11, 1911.

Sir: I have the honor to transmit herewith a paper entitled "The Wilting Coefficient for Different Plants and Its Indirect Determination," by Dr. L. J. Briggs, Physicist in Charge of Physical Investigations, and Dr. H. L. Shantz, Plant Physiologist, of this Bureau, and recommend its publication as Bulletin No. 230 of the Bureau series.

Respectfully,

B. T. Galloway,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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B. P. I.—695.

THE WILTING COEFFICIENT FOR DIFFERENT PLANTS AND ITS INDIRECT DETERMINATION.

INTRODUCTION.

The wide range in moisture content of different soils at the time of wilting of the plant cover appears to have been first clearly recognized by Sachs [1] in 1859. The differences which extreme types of soil exhibit in this respect are truly remarkable, ranging, as we shall show later, from 1 per cent in coarse dune sand to 30 per cent or more in the heaviest types of clay. Sachs's experimental work in this field was confined to a single plant. Later investigators in extending this work concluded that not only do soils show a wide range in moisture retentiveness, but that different groups of plants differ widely in their ability to reduce the moisture content of a given soil. Thus, the experimental work of Gain (1895),[2] Heinrich (1894),[3] Hedgcock (1902),[4] and Clements (1905) [5] all indicates considerable variation in the moisture content of the soil at the time of wilting of different plants, which has been interpreted to mean that some plants are capable of reducing the moisture content of a given soil to a lower point than others; in other words, that the nonavailable moisture varies according to the kind of plant used as an indicator. In fact, this view is the one usually presented in the standard works on plant physiology and plant ecology.

The difference exhibited by plants in this respect has also been considered to be an important factor in drought resistance, the additional supply of water thus made available to some plants being supposed to be sufficient to carry them through a dry period when other plants would succumb to drought. With this point of view in mind the present writers have made an extensive series of determinations with a number of plants, including native plants from semi-

[1] Sachs, J. Bericht über die physiologische Thätigkeit an der Versuchsstation in Tharandt. Landwirthschaftlichen Versuchs-Stationen, 1859, vol. 1, p. 235.

[2] Gain, E. Action de l'Eau du Sol sur la Végétation. Revue Générale de Botanique, vol. 7, 1895, p. 73.

[3] Heinrich, R. Zweiter Bericht über die Verhältnisse und Wirksamkeit der landwirtschaftlichen Versuchs-Stationen zu Rostock, 1894, p. 29.

[4] Hedgcock, G. G. The Relation of the Water Content of the Soil to Certain Plants, Principally Mesophytes. Studies in the Vegetation of the State, pt. 2, 1902, pp. 5-79. In Botanical Survey of Nebraska, vol. 6.

[5] Clements, F. E. Research Methods in Ecology, Lincoln, Nebr., 1905, p. 30.

arid and arid regions, to determine the variation exhibited in their ability to reduce the moisture content of the soil before permanent wilting takes place. The results of these investigations have led us to conclude that the variation exhibited by different plants is much less than has heretofore been supposed and that it is insignificant compared with the range in moisture retentiveness exhibited by different soils.

As the work developed it became evident that many precautions which had not heretofore been observed were necessary in determining accurately the moisture content of the soil corresponding to the wilting point of plants. This led to the development of the wax-seal and balancing methods.

In connection with the study of the moisture requirements of plants in semiarid regions it is necessary to be able to determine quickly the soil-moisture content at the wilting point. This constitutes the datum from which the moisture available for growth can be calculated and without which field determinations of soil moisture are of little value. Owing to the difficulty of making direct determinations in the field of the moisture content corresponding to the wilting point, we have compared the wilting-point determination with the moisture retentiveness of the soil as measured by physical methods, which has resulted in the development of several indirect methods applicable to field conditions. These methods are described in the last part of this paper.

WILTING COEFFICIENT.

If the roots of a plant are well established in a mass of soil the plant gradually reduces the water content until permanent wilting occurs. The water remaining in the soil under this condition has been termed "nonavailable" by previous writers. We have found, however, that plants can reduce the soil-moisture content below the point corresponding to the permanent wilting of the leaves, so that at the wilting point a part of the soil moisture must still be available. In fact, as we shall show later, this loss of water from the soil to the air goes on through the plant tissues even after the death of the plant, and appears to be limited only by the establishment of a state of equilibrium between the soil and the air. The plant during the drying stage acts simply as a medium for the transference of water, and, while the rate of loss is reduced, the final result is the same as if the air and soil were in direct contact.

The nonavailable water in a soil is then, strictly speaking, the soil-moisture content when in equilibrium with the moisture of the air. Such a condition of equilibrium can at best be only approximate, since the saturation deficit of the air is constantly changing with the

temperature. It is important then to recognize that the moisture in a soil is not nonavailable until it has been reduced to the moisture content of air-dry soil. Since growth practically ceases when the plants are in a permanently wilted state, any reduction of the soil moisture below this point constitutes an actual deficit which must be made up before the growth of any plant can be resumed. This deficit may be brought about either by direct evaporation from the soil to the air or by indirect evaporation through the plant when in a wilted or a dying condition.

The permanent wilting of the plant does not then mark any limiting condition in the movement of water from the soil through the plant to the air. It is simply a point on the moisture curve corresponding to which the forces opposing the further removal of soil moisture exceed the osmotic force exerted by the cell contents of the plant. Under such conditions transpiration will exceed absorption—that is, a part of the water transpired will be supplied from that stored in the leaf tissues—and loss of turgor will result. It consequently appears advisable to use a more specific term for the moisture content of the soil corresponding to the wilting point of a plant, and we have employed the term "wilting coefficient" in this sense in the present paper.

The wilting coefficient of a soil is then defined as the moisture content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil-moisture supply. By a permanent reduction is meant a condition from which the leaves can not recover in an approximately saturated atmosphere without the addition of water to the soil. In the case of most plants wilting accompanies this reduction of the water content of the leaves and is the criterion used to determine the wilting coefficient of a soil for that plant. The definition as stated is applicable also to those plants which, owing to structural peculiarities, do not give visible evidence of a reduction of the moisture content of the leaves. The wilting coefficient for such plants is determined by means of the balancing method to be described later.

Two independent variables enter into the determination of the wilting coefficient: (1) The moisture retentiveness of the soil used and (2) the kind of plant used as an indicator. Any determination is therefore to be considered as the wilting coefficient of the particular soil employed for the particular plant used as an indicator.

The nonavailable moisture must, then, strictly be considered as the moisture content of the soil when in equilibrium with the air; while the available moisture is of course represented by the difference

between the actual and the nonavailable water at any time. The water content which is *available for growth* is represented by the difference between the actual moisture content and the wilting coefficient.

WAX-SEAL METHOD FOR DETERMINING THE WILTING COEFFICIENT.

The method which we have employed for determining the wilting coefficient consists essentially (1) in the use of an impervious pot, (2) in sealing over the soil surface in the pot with wax so as to prevent all evaporation from the soil, and (3) in keeping the soil mass at an approximately constant temperature. Under these conditions the percentage of water remaining in the soil at the time the plants wilt is termed the wilting coefficient.

ESSENTIALS IN DETERMINING THE WILTING COEFFICIENT.

In determining the wilting coefficient of a soil we have found that the following precautions should be observed:

(1) The soil mass should be as uniform as possible, since the wilting coefficient varies with the texture of the soil and is consequently affected by stratification or other nonuniformity of the soil mass.

(2) The soil should be brought to a uniform moisture content before being placed in the pots. Otherwise, small volumes of soil may remain dry and thus introduce an error in the final moisture determinations.

(3) All loss of water from the soil should be prevented except that resulting from the transpiration of the plant. Otherwise, the surface soil may dry out below the wilting coefficient before the inner soil mass has reached this limit.

(4) All sudden fluctuations in temperature should be avoided. Otherwise, condensation will occur on the inner walls of the pot as the result of distillation from the soil, due to the difference of temperature. This condensed water will be absorbed by the roots in contact with the inner walls of the pot and the moisture content of the principal soil mass may thus be reduced below the wilting coefficient.

DESCRIPTION OF THE METHOD.

In working out a practical method embodying the above requirements, which have not been fully complied with in the methods heretofore described, we have adopted the following procedure:

(1) The air-dried soil is sifted through a 2-millimeter screen to remove gravel and to insure greater uniformity. The soil, after

sifting, is thoroughly mixed, special care being taken to avoid the separation of the fine and coarse particles. Variation in the amount of gravel and coarse sand in the different pots causes irregularities in the wilting-coefficient determinations, due to the fact that the coarse particles add to the weight of the soil without appreciably contributing to its water-holding properties.

In certain soils, notably those deficient in lime, it is best to add a small amount of calcium carbonate to the soil before planting to insure the growth of the seeds.

(2) The proper amount of water to be added to the air-dried soil is dependent upon the soil texture, varying from 5 per cent for sand to 30 per cent or more for clay. The quantity to be used is best determined by adding water slowly from a graduate to a small weighed portion of soil until a condition of good tilth is reached. A heavy soil can be moistened without puddling by placing it on a slab or table in a cone-shaped pile with a large crater in the top into which the required amount of water is slowly poured. The crater is then filled with dry soil from the sides, and the whole mass is covered to prevent evaporation and allowed to stand until the water permeates the mass. The soil is then thoroughly mixed. During the process of mixing it is sifted through a screen of ¼-inch mesh so as to remove any pellets of soil having more than their proportionate amount of water. After mixing, the moist soil should be kept in a tight receptacle until ready for use.

Impervious pots must be used, of course, in order to prevent the soil in contact with the pots from drying out below the wilting coefficient. We have found that ordinary straight-walled drinking glasses are very satisfactory for this work when seedling plants are used. During the process of filling, the soil is slightly compacted by jarring the bottom of the glass against the hand. Three to five seeds are planted in each pot, about 1 centimeter in depth, after which the surface soil is smoothed and compacted slightly. The soil surface after planting should be about 1 centimeter below the edge of the glass. It is often advantageous to plant seeds which have just begun to germinate. This method insures a perfect stand and avoids excessive respiration beneath the wax seal.

(3) In sealing the pots the wax is heated slightly above the melting point and a sufficient amount is poured into the pot to cover the soil surface to a depth of about 3 millimeters. The pot is rocked slightly so as to bring the wax into thorough contact with the inner walls of the pot, after which the excess wax is poured off. If the wax is at the proper temperature this will give a perfect and uniform seal over the entire surface. If the seal is not perfect the process is repeated. The wax layer should be approximately 1 millimeter in thickness and

should be in close contact with the soil. If the wax does not adhere to the soil surface the pots should be resealed, since the plants may buckle under the wax cover if it is not adherent.

In the case of monocotyledons we have found that the wax seal can best be added immediately after planting the seeds. On germination these plants will grow readily through the wax, which forms a perfect seal around the stems. (Pl. I.) In the case of dicotyledons it is advisable to keep the pots in a moist chamber to reduce evaporation until the seedlings appear above the ground, when the wax seal can be applied without injury to the plants.

Even in the case of dicotyledons this wax seal is often applied at the time of planting. This prevents the soil from drying out between the time of planting and complete germination. Plants which do not raise the cotyledons above the soil surface and those with very small seeds often push through the wax without breaking the seal. Other dicotyledons push their way through the wax cover without any difficulty, although it is often necessary to reseal these pots after the seedlings are all up, especially in the case of plants with large cotyledons, such as the bean, squash, cucumber, etc.

Aeration, when necessary, can readily be accomplished by making two small holes through the wax to the bottom of the pot on opposite sides. A glass tube drawn to a small opening and connected with a wash bottle is forced into one hole to supply moist air, and a similar glass tube is forced into the opposite opening and attached to an aspirator to withdraw the air from the pot. The wax forms a perfect seal around the glass tubes. In this way many pots can be aerated and the holes resealed with a hot wire in a comparatively short time.

The wax-seal method is also particularly adapted to the study of transpiration, since by its use all loss of water is avoided except that taking place through the plant tissues. This fact has been determined by repeated measurements.

(4) Serious fluctuations in temperature can be avoided by immersing the pots to within 5 millimeters of the top in a tank of water in which a circulation is constantly maintained. An apparatus for this purpose which has been found very convenient is shown in figure 1. It consists of a copper tank 36 inches wide, 72 inches long, and 4 inches deep, which is divided by means of a series of longitudinal partitions into 10 compartments. These partitions are open at alternate ends, so that a stream of water introduced at one side of the tank flows back and forth the full length of the tank 10 times before finally reaching the exit on the opposite side. The water is thus kept constantly in motion around the pots.

The circulation of water is effected by means of a small centrifugal pump, as shown in the illustration. This pump takes water from the

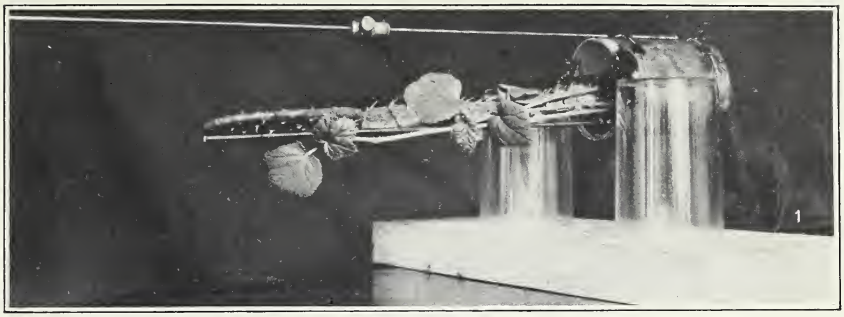

FIG. 1.—BALANCED SYSTEM CONTAINING OPUNTIA AND SQUASH. FIGS. 2 AND 3.—POTS SEALED WITH WAX, SHOWING KUBANKA WHEAT SEEDLINGS PUSHING THROUGH THE WAX SEAL. THE WAX IS APPLIED IMMEDIATELY AFTER PLANTING THE SEEDS.

bottom of the wooden supply tank, so that a complete circulation of water is maintained throughout the whole system. The water level is automatically regulated, since the amount of water delivered by the centrifugal pump is lessened as the head against which the pump operates is increased. The opening from the immersion tank is so situated as to be partly above the level of the water, and all dust and impurities collecting on the water surface are thus swept into the supply tank, leaving the water in the immersion tank perfectly clear. The apparatus as figured is capable of holding 250 glass pots, and has given excellent service in the experiments in which it has been employed.

As soon as the plants in a pot have been reduced to a wilted condition from which they can not recover when placed in a damp chamber,

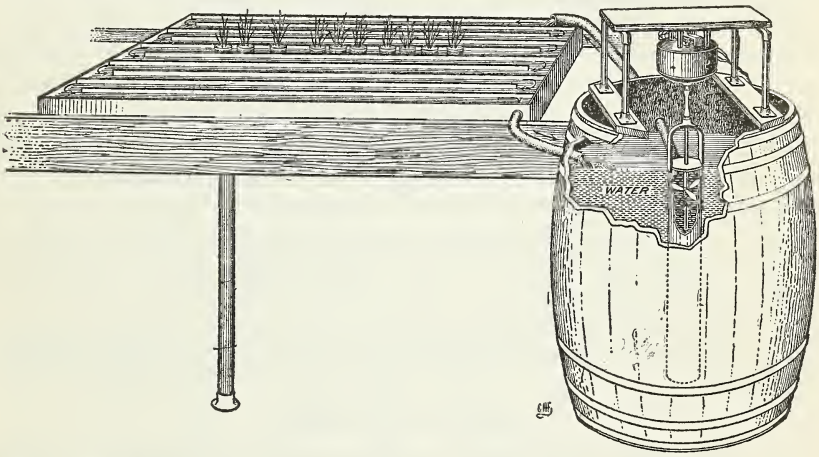

FIG. 1.—Apparatus for preventing sudden changes in temperature during the determinations of the wilting coefficient. The propeller in the central tube causes a constant circulation of the water around the pots.

the water content of the soil is determined. The soil mass can usually be removed intact by breaking the wax seal around the walls of the pot and gently jarring the edge of the inverted pot against the bench. The lower two-thirds of the soil mass is taken for the moisture determination, since the roots do not usually develop so extensively in the upper portion. The moisture determination is based upon the loss of water taking place when the soil is dried to constant weight at 100° C., the percentage of moisture being based upon the dry weight of the soil.

COMPOSITION OF THE WAX SEAL.

For sealing the pots, paraffin, petrolatum, beeswax, and tallow were tried in various proportions. A wax composed of 80 per cent paraffin (melting point 45° C.) and 20 per cent petrolatum was found

to be most satisfactory for use at ordinary temperatures, the exact proportions being unimportant. This mixture melts at so low a temperature and has such a low heat conductivity that it can be poured into a pot around the most delicate seedlings without injury. This feature is important in experimenting with delicate dicotyledons. On cooling, this wax adheres well to the glass and to the soil, forming a perfect seal. Other mixtures, notably those containing beeswax, show a decided tendency to separate from the glass on cooling, necessitating the resealing of the edges with a hot iron.

None of the substances mentioned give good results when used alone. Soft paraffin (45°) stretches, petrolatum creeps, and beeswax, tallow, and the higher paraffins crack. Except when soft paraffin is used, the plants show no difficulty in penetrating the wax cover, even when a wax as hard as that with which the ordinary commercial phonograph records are made is employed as a seal.

During the winter in the greenhouse the paraffin-petrolatum mixture gives excellent results even when left in direct sunlight. During the warm portion of the year, however, direct sunlight is likely to melt this wax and in this way break the seal and cause damage to the plants, due to the wax creeping over the plant surface. This creeping does not occur if the pots are kept in the temperature-control tank. A mixture of 10 to 30 per cent of beef tallow with beeswax or of 8 to 12 per cent of petrolatum with beeswax has been found to be an excellent material for use in warm weather both in the greenhouse and for out-of-door work.

Modeling clay has also been used to seal the pots, but it is not so easily applied as the wax and is not suitable for use with delicate seedlings.

EXPERIMENTAL ERROR.

In determining the wilting coefficient of a given soil for a particular plant some variation will be found in the results obtained from the individual pots. This variation appears to be due in part to the lack of uniformity of the soil in the different pots, but mainly to the fact that in some pots the roots are distributed through the soil mass much more uniformly than in others. When the root distribution is defective, the mean distance through which the soil moisture must move through capillary action is greater. Since capillary movement becomes very slow as the moisture content approaches the wilting coefficient, these portions of the soil not penetrated by roots will have a somewhat higher moisture content. The wilting coefficient determination in the case of an imperfect root distribution will consequently be somewhat too high. On the other hand, errors arising from the distillation of water on the walls of the pot will result in giving a wilting coefficient below the true value.

Some uncertainty also arises in connection with the determination of the wilting point. Plants often wilt during the day and recover

during the night. The wilting of a plant in the hot part of the day is, therefore, not conclusive evidence that moisture is not available. A wilted condition in the early morning is considered the best proof that the moisture content has been reduced to the true wilting point. Check determinations were repeatedly made by placing the pots containing wilted plants under a bell jar in nearly saturated air. These plants were unable to recover their turgidity. Since the wilting point is influenced to some extent by sudden changes in the temperature and humidity of the air of the plant house, these conditions should be determined and kept as uniform as possible during the growth of the plants.

The degree of accuracy which may reasonably be expected with the wax-seal method when suitable precautions are taken is shown by the series of determinations presented in Table I, which gives the wilting coefficient for Kubanka wheat in each of several pots for three types of soil. The plants were grown in an ordinary plant house, where the average temperature was about 70° F. and the relative humidity about 85 per cent.

TABLE I.—*Individual pot measurements of the wilting coefficient of three types of soil for Kubanka wheat.*

Plant.	Wilting coefficient of—			Plant.	Wilting coefficient of—		
	Fine sand.	Fine sandy loam.	Clay loam.		Fine sand.	Fine sandy loam.	Clay loam.
Kubanka wheat	2.6	.....	16.9	Kubanka wheat	2.6	9.8	16.3
Do	2.1	.....	16.8	Do	2.5	9.3	16.3
Do	2.7	.....	16.4	Do	2.7	9.7	16.7
Do	2.8	9.7	16.2	Do	2.7	9.4	16.3
Do	2.6	9.3	15.5				
Do	2.7	9.9	15.7	Mean	2.59	9.66	16.3
Do	2.7	10.1	17.3	Probable error of mean	± .03	± .05	± .09
Do	2.6	9.7	16.7				
Do	2.5	9.4	15.6	Probable error of single observation	± .11	± .18	± .34
Do	2.6	9.6	16.0				
Do	2.4	9.3	16.0				
Do	2.7	9.4	16.2				

Table I shows the individual determinations in each series, together with the arithmetical mean, the probable error of the mean, and the probable error of a single observation. The term "probable error" is used in its usual mathematical sense, that is to say, in the case of the series of determinations in sand the chances are even that if the series were repeated the mean would lie between the values 2.56 and 2.62; and if the experiment were repeated with a single pot, the chances are even that the wilting coefficient for this pot would fall between 2.48 and 2.70. The probable error of the mean is about one two-hundredths, and that of a single observation one-fiftieth of the actual wilting coefficient of the loam and clay soils, while the corresponding probable errors in the case of sand are about twice as great. It appears, therefore, that while there is

considerable variation in individual pots, the mean of a suitable series represents the wilting coefficient of a given soil with an accuracy equal to the accuracy with which the moisture retentivity of the soil can be measured by purely physical methods.

COMPARISON OF THE SOIL-MOISTURE CONTENT AT THE WILTING POINT AND THE DEATH POINT.

Emphasis has already been placed upon the fact that the wilting point does not mark the minimum limit of moisture that is available to the plant. The experimental data upon which this conclusion was based are given in Tables II and III. Determinations were made of the soil-moisture content at the wilting point and at the death point for each individual culture. In every instance a marked reduction of the water content was noted after the plants wilted.

The data given in Table II were obtained with Kubanka wheat seedlings grown in sealed pots. The pots were kept in a temperature-control tank until the plants wilted. The weight of each pot was then taken. Some of the pots were then transferred to a dark constant-temperature room, while the remainder were left in the control tank. After the plants had died, the pots were again weighed and moisture determinations made upon the whole sample. The difference in weight corrected for the loss in weight of the plants gave the necessary data for calculating the wilting coefficient.

TABLE II.—*Comparison of the wilting coefficient and the water content at death point for Kubanka wheat seedlings in soil No. 26.*

Observation.	Plants allowed to die in temperature-control tank in greenhouse.		Observation.	Plants allowed to die in dark room at constant temperature.	
	Wilting coefficient.	Moisture content at death point.		Wilting coefficient.	Moisture content at death point.
1	7.9	7.3	1	8.5	8.3
2	8.3	7.4	2	8.1	7.7
3	8.0	7.4	3	8.4	8.0
4	8.3	7.1	4	8.1	6.9
5	8.1	7.4	5	7.9	7.3
6	8.3	7.5	6	8.0	7.7
7	8.3	7.9	7	8.2	7.5
8	7.8	7.5	8	8.5	8.2
9	8.3	7.5	9	7.9	7.7
10	8.0	7.6			
11	8.5	7.7			
12	8.7	7.7			
13	8.6	7.6			
14	8.6	6.7			
15	8.2	7.5			
16	8.5	7.8			
17	7.8	7.5			
18	8.0	7.3			
19	7.5	7.3			
Mean	8.2	7.5	Mean	8.2	7.7
Probable error of mean	± .05	± .04	Probable error of mean	± .05	± .10
Probable error of single observation.	± .21	± .18	Probable error of single observation.	± .16	± .30

The means of the determinations given in Table II show that in the interval between wilting and death the plants reduced the soil moisture 0.7 per cent, or to 92 per cent of the moisture content at the wilting point. The loss from the dying plants in the constant-temperature room was somewhat less, due to a smaller saturation deficit.

Another similar series of determinations was made for Kubanka wheat and for water cress, except that the observations were extended to include the period following the death of the plants. The results are given in Table III.

TABLE III.—*The water content of the soil in sealed pots at the wilting point, at the death point, and at a later period for Kubanka wheat and for water cress.*

Designation of pot.	Wilting point.	Time interval in days.	Death point.	Time interval in days.	Final per cent.
Kubanka wheat:					
4	7.0	28	5.2	126	3.1
6	7.9	25	5.9	126	2.6
7	7.0	25	5.5	126	3.5
8	6.6	19	6.4	126	4.9
9	7.1	27	5.9	134	4.8
10	7.8	27	6.9	134	5.9
11	6.9	19	5.9	126	4.3
12	7.3	27	6.6	134	5.7
13	8.0	27	6.9	37	6.1
14	7.3	27	6.2	134	4.9
Mean	7.3	.....	6.2	.....	4.6
Probable error of mean	± .10	.....	± .12	.....	.....
Probable error of single observation	± .33	.....	± .39	.....	.....
Water cress:					
1	7.6	7	6.0	51	4.6
2	7.8	7	6.5	129	2.4
3	7.7	7	6.3	129	4.3
5	6.5	10	5.5	119	4.2
Mean	7.4	.....	6.1	.....	3.9

The plants were grown in sealed pots containing about 250 grams of soil. Column 2 of the table gives the water content of the soil corresponding to the wilting of the plants. Column 3 gives the number of days intervening between the wilting and the death of the plants, at which time the moisture content of the soil had been materially reduced, as shown in column 4. A still greater loss of water occurred during the subsequent period, at the end of which the moisture content of the soil had been reduced to the point indicated in column 6. The mean moisture content of the soil at the death point of Kubanka wheat had been reduced to 85 per cent of the water content at the wilting point, while the mean soil-moisture content at the end of the experiment was only 63 per cent of that at the wilting point. An even greater reduction occurred in the pots containing the water cress.

It is evident, then, from the data already presented that water is being steadily removed from the soil by dying or dead plants and

that a limit is reached only when the soil moisture comes into approximate equilibrium with the moisture content of the air. The soil-moisture content at the wilting point can not then be considered as nonavailable to the plant, and for this reason has been designated in the present paper as the wilting coefficient.

In a recent paper[1] the writers referred to a proposed investigation of the relative advantages of the wilting point and the death point of plants as criteria in comparing plants in their relation to soil moisture. The data given in Tables II and III provide a basis for comparing these criteria. A comparison of the probable errors for single determinations is the most satisfactory way to judge of the relative accuracy. These errors are given in Table IV, expressed as a percentage of the numbers which they affect. That part of Table III referring to water cress does not contain sufficient observations to give a probable error of any significance.

TABLE IV.—*Relative magnitude of the probable errors of a single observation using the wilting point and the death point as criteria.*

Designation of data.	Number of observations.	For wilting point.	For death point.
		Per cent.	*Per cent.*
Wheat, control tank, Table II	19	2.5	2.4
Wheat, dark room, Table II	9	2.0	3.9
Wheat, Table III	10	4.5	6.3
Mean		3.0	4.2

It will be seen from Table IV that the average error in determining the wilting coefficient is considerably less than that accompanying the determination of the moisture content corresponding to the death point. Death-point determinations showing a very satisfactory agreement can, however, be obtained with seedlings by the use of the temperature-control tank, as shown by the results given in the first part of Table II. But other and more important considerations combine to make the wilting point decidedly superior to the death point as a physiological criterion of soil-moisture conditions. The wilting coefficient is practically independent of the kind of plant used as an indicator, as will be shown later, while the death point varies with the plant used, some plants dying much more quickly after wilting than others. The time required for a determination is also shortened by using the wilting point. But the great advantage of using the wilting point is that it practically marks the cessation of growth and so constitutes a datum from which the water content available for growth in a particular soil may be determined

[1] Briggs, L. J., and Shantz, H. L. A Wax Seal Method for Determining the Lower Limit of Available Soil Moisture. Botanical Gazette, vol. 51, 1911, pp. 210-219.

when the total water content is known. This could not be determined directly by means of death-point observations, but would require a correction term more or less dependent upon the plant used.

EFFECT OF THE AGE OF THE PLANT ON THE WILTING COEFFICIENT.

In making wilting-coefficient determinations it is much more convenient to use seedlings than old plants. The question then arises as to whether determinations made with seedlings as indicators represent the moisture content of the soil corresponding to the wilting point of more mature plants. The determinations given in Tables V and VI were made with reference to this point.

A series of experiments with Kubanka wheat plants, six soils in each series, using plants of three different ages, is given in Table V. The actual wilting-coefficient determinations for each soil are given, together with the ratio of each individual determination to the mean of each soil. The ratios indicate a slightly higher wilting coefficient for the younger plants, the means being 1.01 for plants 20 to 30 days old, 0.99 for plants 75 to 80 days old, and 0.98 for plants 104 days old. This is what would take place if the concentration of the leaf-cell contents increased with the age of the plants. The same effect would, however, be brought about by the more uniform root penetration in the case of the older plants, or by an increase in woody tissue in the leaves which would tend to retard the appearance of wilting. Furthermore, when the differences are considered in connection with their mean probable errors it becomes evident that the influence of the age of the plants upon the wilting point is very slight.

TABLE V.—*Effect of the age of wheat plants on the wilting coefficient.*

Soil number.	Wilting coefficients of plants at stated ages.					
	20 to 30 days.		75 to 80 days.		104 days.	
	Actual.	Ratio, actual to average.	Actual.	Ratio, actual to average.	Actual.	Ratio, actual to average.
1	0.86	1.00	0.80	0.93	0.78	0.91
	.86	1.00	.87	1.01	.88	1.02
	1.00	1.16	.....	.....	.....	.....
	.80	.93	.....	.....	.....	.....
2	2.5	.97	2.7	1.04	2.7	1.04
	2.7	1.04	.....	.....	.....	.....
	2.8	1.08	.....	.....	.....	.....
	2.6	1.00	.....	.....	.....	.....
	2.7	1.04	.....	.....	.....	.....
	2.7	1.04	.....	.....	.....	.....
	2.6	1.00	.....	.....	.....	.....
	2.6	1.00	.....	.....	.....	.....
	2.5	.97	.....	.....	.....	.....
	2.6	1.00	.....	.....	.....	.....
	2.4	.93	.....	.....	.....	.....
	2.7	1.04	.....	.....	.....	.....
	2.6	1.00	.....	.....	.....	.....

TABLE V.—*Effect of the age of wheat plants on the wilting coefficient*—Continued.

Soil number.	Wilting coefficients of plants at stated ages.					
	20 to 30 days.		75 to 80 days.		104 days.	
	Actual.	Ratio, actual to average.	Actual.	Ratio, actual to average.	Actual.	Ratio, actual to average.
3	5.1	1.07	4.6	0.97	4.3	0.90
	4.9	1.03	.....	.....	4.6	.97
	4.9	1.03	.....	.....	.....	.....
	4.7	.99	.....	.....	.....	.....
	5.0	1.05	.....	.....	.....	.....
	4.7	1.03	.....	.....	.....	.....
4	9.7	1.01	9.3	1.01	9.3	.97
	9.7	1.01	9.4	.98	9.3	.97
	9.9	1.03	9.4	.98	9.4	.98
	10.1	1.05	.....	.....	.....	.....
	9.7	1.01	.....	.....	.....	.....
	9.8	1.02	.....	.....	.....	.....
	9.6	1.00	.....	.....	.....	.....
5	14.1	1.01	13.7	.99	13.7	.99
	14.7	1.06	14.0	1.00	13.4	.96
	14.3	1.03	.....	.....	14.0	1.00
	14.7	1.06	.....	.....	.....	.....
	13.4	.96	.....	.....	.....	.....
	14.6	1.05	.....	.....	.....	.....
	13.1	.94	.....	.....	.....	.....
	13.5	.97	.....	.....	.....	.....
6	16.3	1.00	16.2	.99	16.2	.99
	16.9	1.04	16.3	1.00	16.3	1.00
	16.8	1.03	16.7	1.02	16.7	1.02
	16.4	1.01	.....	.....	.....	.....
	15.5	.95	.....	.....	.....	.....
	15.7	.96	.....	.....	.....	.....
	17.3	1.06	.....	.....	.....	.....
	15.6	.96	.....	.....	.....	.....
	16.0	.98	.....	.....	.....	.....
	16.0	.98	.....	.....	.....	.....
Mean	.....	1.01	.....	.99	.....	.98
Probable error of mean	.....	± .004	.....	± .005	.....	± .007
Probable error of a single determination	.....	± .028	.....	± .019	.....	± .026

Similar determinations were made with seedlings and old grass plants, but the same species were not available for use in both experiments. These determinations are given in Table VI. The soil used throughout these determinations was the same, so that the observed wilting coefficients can be directly compared. In this case the seedlings gave a slightly lower mean wilting coefficient than the older plants. This is probably due to the slightly better root distribution on the part of the seedlings, which were planted rather thickly. The difference, however, is only 0.2 ±0.1 per cent,[1] so that the determinations are in practical agreement.

[1] The probable error of the difference of two numbers, each of which is affected with a probable error, is equal to the square root of the sum of the squares of the two probable errors.

TABLE VI.—*Comparison of the wilting coefficient for seedling and old grass plants.*

Species.	Old plants.	Species.	Seedlings.
Agropyron tenerum	8.7	Bromus inermis	9.4
Do	9.6	Do	8.8
Do	9.6	Do	9.6
Do	10.4	Do	10.2
Do	9.7	Do	9.5
Do	10.9	Do	9.5
Do	10.3	Do	9.7
Do	10.5	Do	8.9
Do	8.8	Do	9.5
Do	8.4	Do	9.3
Do	9.3	Do	8.6
Do	9.0	Do	9.0
Do	9.3	Do	9.5
Do	9.7	Do	9.5
Do	9.0	Do	9.1
Do	9.9	Do	8.9
A. cristatum	9.2	Do	9.5
Do	9.6	Do	9.1
Do	9.2	Do	8.9
Do	8.9	Do	10.1
Do	8.7	Do	9.5
A. smithii	10.1	Do	10.3
Do	9.6	Do	9.3
Do	10.2	Do	9.0
Do	9.8	Do	9.3
Do	9.5	Do	9.0
Do	9.4	Do	9.3
Do	10.6	Do	9.6
Do	10.7	Do	9.4
Do	9.7	Do	9.5
Do	9.7	Do	9.9
Do	11.4	Do	10.1
		Do	9.8
		Elymus canadensis	9.6
		Do	9.7
		Do	9.6
		Stipa vaseyi	9.3
		Do	9.6
		Do	9.7
		Sitanion hystrix	9.2
		Do	9.6
		Do	9.3
		Aristida longiseta	9.5
		Do	9.7
Mean	9.7	Mean	9.5
Probable error of mean	± .09	Probable error of mean	± .04
Probable error of single determination	± .46	Probable error of single determination	± .25

Difference of means, 0.2±0.1.

Table VII gives a summary covering all the wilting-coefficient determinations made upon seedlings and old plants. The data upon which this summary is based are given in detail in later tables, and only the ratios showing the relative differences in the wilting coefficient are here given for each crop. Reference to the weighted means [1] will show that the mean ratio of the wilting coefficient for old plants is 0.03 higher than the mean ratio obtained for seedlings.

We may conclude then that the wilting coefficient is the same, within the limits of experimental error, for a plant in all stages of development. In other words, the soil-moisture content at the wilting point is not dependent to any material degree upon the age of the plant.

[1] In determining the final mean value, each ratio was included once for each determination used in establishing that ratio.

TABLE VII.—*Summary of wilting coefficient for seedlings and old plants.*

Crop.	Seedlings.		Old plants.	
	Number of observations.	Mean wilting coefficient.	Number of observations.	Mean wilting coefficient.
Corn	75	1.03		
Sorghum	66	.98		
Millet	48	.97		
Wheat	626	.994	27	0.98
Oats	46	.995		
Barley	60	.97		
Rye	19	.94		
Rice	21	.94		
Grasses	44	.96	33	1.00
Legumes	119	1.01	19	1.02
Cucurbits	17	.99		
Tomato	20	1.06		
Colocasia			19	1.13
Hydrophytes			8	1.10
Mesophytes	21	1.03	14	1.02
Xerophytes			16	1.06
Weighted mean		1.00		1.03

EFFECT OF ENVIRONMENTAL CONDITIONS ON THE WILTING COEFFICIENT.

A series of determinations has been made to ascertain the influence of certain environmental conditions, particularly humidity, light intensity, and soil-moisture content upon the wilting coefficient. These determinations are given in Tables VIII, IX, and X, and indicate that the wilting coefficient is not materially influenced by the dryness of the air, by moderate changes in the solar intensity, or by differences in the amount of soil moisture available during the period of growth.

HUMIDITY.

Table VIII gives a comparison of the wilting coefficient obtained for Kubanka wheat grown from the outset in a dry greenhouse and in a glass damp chamber. All determinations were made with the same soil. Considerable variation is shown in the individual observations, which is apt to be the case where plants are subject to extreme conditions. The high determinations are probably due to imperfect root distribution. The mean value of the two series of determinations is the same, indicating that the wilting coefficient is not influenced to an appreciable extent by the saturation deficit.

A plant wilts when transpiration exceeds absorption. Transpiration may be decreased by reducing the transpiring area as well as by increasing the humidity of the air. Absorption may likewise be increased by increasing the root area. Bergen[1] has shown that when plants grown under humid conditions are transferred to a dry atmosphere they transpire water much more rapidly per unit area

[1] Bergen, J. Y. The Modifiability of Transpiration in Young Seedlings. Botanical Gazette, vol. 48, 1909, p. 282.

than the same plants grown in a dry atmosphere. There are, then, three ways in which a plant may respond to a dry atmosphere, i. e., by increasing root area, by decreasing leaf area, and by decreasing transpiration capacity per unit area of leaf surface. In addition to the responses noted above, we have found a decided reduction in transpiration immediately preceding and during the period of wilting. These modifications combine to minimize the effect of a high saturation deficit on the wilting coefficient of a soil when plants are grown from the outset under the conditions under which they finally wilt. Although the assumption has been made[1] that the wilting point will be proportionately higher in an arid than in a humid region, our results both in the laboratory and in the field (see p. 63) indicate that this is not the case.

TABLE VIII.—*Comparison of the wilting coefficient for Kubanka wheat in a dry greenhouse and in a glass damp chamber.*

In dry greenhouse.						In damp chamber.	
Observation.	Coefficient.	Observation.	Coefficient.	Observation.	Coefficient.	Observation.	Coefficient.
1	8.9	23	9.7	45	9.0	1	9.6
2	9.0	24	9.5	46	9.4	2	9.1
3	10.0	25	9.4	47	11.4	3	9.2
4	10.7	26	9.6	48	11.7	4	9.6
5	10.0	27	9.7	49	10.2	5	11.0
6	10.2	28	9.6	50	8.8	6	10.7
7	10.2	29	8.9	51	9.3	7	8.4
8	10.0	30	9.6	52	9.1	8	11.1
9	10.0	31	9.4			9	9.9
10	9.1	32	9.9			10	11.0
11	8.2	33	10.7			11	8.5
12	9.0	34	10.2			12	7.8
13	9.2	35	8.8			13	9.9
14	9.1	36	8.1			14	9.0
15	9.8	37	8.4			15	8.6
16	9.0	38	9.3			16	9.8
17	10.5	39	10.1				
18	9.7	40	9.0	Mean	9.6	Mean	9.6
19	9.8	41	9.3	Probable error of mean	± .072	Probable error of mean	± .17
20	9.6	42	9.2				
21	11.1	43	9.6	Probable error of single observation	± .52	Probable error of single observation	± .68
22	8.9	44	11.4				

LIGHT INTENSITY.

The observations given in Table IX were made to determine the effect of light intensity on the wilting coefficient. The shade used was a single thickness of cheesecloth, which reduced the intensity of direct sunlight to about one-half normal. It will be seen from this table that the two series of observations are in substantial agreement, the mean difference of the two series being only 0.2 ± 0.11 per cent. These results indicate that a considerable change in the light intensity has no marked effect upon the value of the wilting coefficient.

[1] Free, E. E. Studies in Soil Physics. Plant World, vol. 14, 1911, pp. 116–118.
Livingston, B. E. Relation of Soil Moisture to Desert Vegetation. Botanical Gazette, vol. 50, 1910, p. 251.

TABLE IX.—*Effect of sun and shade on the wilting coefficient for Kubanka wheat in soil No. 26.*

Observation.	Sun.	Shade.	Observation.	Sun.	Shade.
1	8.9	9.0	10	.....	9.1
2	9.1	8.7	11	.....	9.7
3	9.3	9.1			
4	8.8	10.0	Mean	9.2	9.4
5	9.5	9.8	Probable error of mean	± .063	± .09
6	8.9	9.1	Probable error of single observation	± .19	± .29
7	9.4	9.3	Difference of means	.....	0.2±0.11
8	9.5	9.9			
9	9.4	9.7			

RELATION OF SOIL-MOISTURE CONTENT DURING GROWTH TO THE WILTING COEFFICIENT.

The observations recorded in Table X were made to determine whether the wilting coefficient was influenced by the amount of soil moisture available to the plant during its period of growth. The experiments were made with Turkey Red and Bluestem wheat. The water content of the soil during the period of growth was maintained practically constant in each pot, the pots being weighed daily and water added to replace that which had transpired. The moisture content of the different pots during the period of growth ranged from 12 to 36 per cent, as shown in column 1 of the table. The plants were grown for a period of 61 days. Watering was then discontinued and the plants were allowed to wilt, when moisture determinations were made. The results of the wilting-coefficient determinations are given in columns 2 and 4 of the table, and the departure of each determination from the mean of the series is shown. The distribution of the plus and minus departures gives no indication that the initial moisture content has any influence on the wilting coefficient.

TABLE X.—*Effect of different moisture contents during the period of growth (61 days) on the wilting coefficient for wheat in soil No. 4.*

Water content during period of growth (per cent).	Turkey Red wheat.		Bluestem wheat.	
	Coefficient.	Departure from mean.	Coefficient.	Departure from mean.
12	.....	.....	8 8	−0.2
14	8.8	−0.5	8.9	− .1
16	9.5	+ .2	8.7	− .3
18	9.6	+ .3	9.4	+ .4
20	9.8	+ .5	9.6	+ .6
22	9.1	− .2	9.5	+ .5
24	9.0	− .3	9.4	+ .4
26	10.0	+ .7	9.0	.0
28	9.7	− .4	9.2	+ .2
30	8.5	− .8	7.9	−1.1
32	9.6	+ .3	8.0	−1.0
34	.....	.....	9.2	+ .2
36	8.5	− .8	.....	.....
Mean	9.3	.....	9.0	.....
Probable error of mean	± .011	.....	± .011	.....
Probable error of single observation	± .36	.....	± .37	.....

WILTING COEFFICIENTS FOR DIFFERENT PLANTS GROWN IN A SERIES OF SOILS

It is evident that in determining the wilting coefficients for different plants great care must be used to provide uniform soil for the growth of the plants, since a variation in the moisture retentivity of the soil would lead to erroneous conclusions regarding the relative ability of two plants to remove moisture. Furthermore, it is desirable to make such comparative determinations in a number of soils of widely differing texture and composition in order to eliminate a possible influence of the soil used upon the final comparisons. Table XI gives the wilting-coefficient determinations for a large number of plants grown in a series of soils, and embraces experimental work carried on during a period of three years. Many of the determinations were made before the necessity of some of the precautions which have been mentioned in the first part of the paper were fully appreciated; consequently there is a greater fluctuation in the results of the individual determinations than otherwise would have occurred.

The determinations have been carried on in 20 different soils, ranging from a coarse sand to a clay loam, and the data as presented include all determinations which have been made upon these soils. The determinations for the different plants are grouped with respect to the soil in which the determinations were made, the soils being arranged in the order of increasing wilting coefficients. A direct comparison of the wilting coefficient obtained for different plants with the same soil can thus be readily made without reducing the observations in any way. In using so many different plants the number of observations made with each plant have necessarily been limited, and too much emphasis should not be placed upon the differences shown in the mean values of short series in which the number of observations has been insufficient to establish the probable error. It should also be borne in mind that the probable error indicates only the accidental errors. Constant errors, due to any cause, such as an inadequate root distribution in certain species of plants, would appear as real differences in the wilting-coefficient determinations for the different plants, and such errors would not be indicated by the probable error.

TABLE XI.—*Wilting coefficients of various soils for different plants.*

Soil and species or variety of plant.	Coefficient.
Soil No. 1 (sand). Moisture equivalent 1.55.	
Wheat: Kubanka, G. I. 1440	0.86
Do	.86
Do	1.00
Do	.90
Do	.80
Do	.80
Do	.87
Do	.78
Do	.88
Mean	.86
Probable error of mean	± .02
Probable error of single observation	± .05
Sorgo: Red Amber, S. P. I. 17543	.87
Do	.79
Mean	.83
Mean for all determinations, soil No. 1	.86
Probable error of mean	± .02
Probable error of single observation	± .05
Soil No. 7 (coarse sand). Moisture equivalent 1.55.	
Corn: Boone County White, C. I. 119	1.05
Do	1.02
Do	1.13
Mean	1.07
Corn: Esperanza, M. 66	1.11
Do	1.04
Mean	1.08
Sorghum: White durra, S. P. I. 24997	1.05
Do	.91
Do	.95
Mean	.97
Sorghum: Dwarf milo, S. P. I. 24970	.96
Do	.92
Mean	.94
Sorgo: Black Amber, Minn. 341	.87
Do	.80
Do	.79
Mean	.82
Wheat: Kubanka, G. I. 1440	1.15
Do	.82
Do	.86
Do	.86
Do	1.00
Do	.90
Da	.80
Do	.80
Do	.87
Do	.78
Do	.88
Mean	.88
Probable error of mean	± .03
Probable error of single observation	± .09
Wheat: Bluestem, Minn. 169	.89
Do	.98
Mean	.94

Soil and species or variety of plant.	Coefficient.
Soil No. 7 (coarse sand). Moisture equivalent 1.55—Continued.	
Oats: Kherson, G. I. 459	1.15
Do	1.10
Do	.95
Mean	1.07
Oats: Swedish Select	.96
Barley: Beldi, G. I. 190	1.04
Do	1.04
Mean	1.04
Barley: Hannchen, G. I. 531	1.18
Do	1.00
Do	.91
Mean	1.03
Rye: Giant Winter	1.02
Do	.81
Do	.90
Mean	.91
Rice: Japan	.97
Do	.95
Mean	.96
Squash: Yellow Summer Crookneck	1.23
Do	1.18
Mean	1.21
Pea: Canada field, S. P. I. 19389	.90
Do	1.01
Do	1.06
Do	1.10
Mean	1.02
Vetch: Vicia faba, S. P. I. 15428	1.22
Tomato: Livingston's Golden Queen	1.08
Do	1.14
Mean	1.11
Tomato: Stone	1.10
Clover: Red	1.00
Colocasia	1.20
Do	1.00
Do	1.20
Mean	1.13
Mean for all determinations, soil No. 7	1.03
Probable error of mean	± .01
Probable error of single observation	± .08
Soil No. 87 (sand). Moisture equivalent 2.48.	
Vetch: Vicia villosa	1.24
Do	1.10
Mean	1.17
Vetch: Vicia faba, S. P. I. 15428	1.49
Do	1.47
Do	1.06
Mean	1.34

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 87 (sand). Moisture equivalent 2.48—Continued.	
Pea: Canada field, S. P. I. 19389	1.16
Do	1.27
Do	1.05
Mean	1.16
Mean for all determinations, soil No. 87	1.23
Probable error of mean	± .041
Probable error of single observation	± .117
Soil No. 2 (fine sand). Moisture equivalent 4.66.	
Wheat: Kubanka, G. I. 1440	2.5
Do	2.7
Do	2.8
Do	2.6
Do	2.7
Do	2.7
Do	2.6
Do	2.6
Do	2.5
Do	2.6
Do	2.4
Do	2.7
Do	2.6
Do	2.7
Do	2.7
Mean	2.6
Probable error of mean	± .02
Probable error of single observation	± .09
Sorgo: Red Amber, S. P. I. 17543	2.3
Do	2.6
Do	2.3
Mean	2.4
Mean for all determinations, soil No. 2	2.6
Probable error of mean	± .02
Probable error of single observation	± .10
Soil No. 8 (fine sand). Moisture equivalent 5.5.	
Corn: Boone County White, C. I. 119	3.3
Do	2.7
Do	3.4
Mean	3.1
Corn: Esperanza, M. 66	3.5
Do	3.7
Mean	3.6
Sorghum: White durra, S. P. I. 24997	3.2
Do	2.5
Do	3.3
Mean	3.0
Sorghum: Dwarf milo, S. P. I. 24970	3.6
Do	3.5
Do	3.8
Mean	3.6
Wheat: Kubanka, G. I. 1440	2.9
Do	3.5
Do	3.5
Mean	3.3
Soil No. 8 (fine sand). Moisture eqvivalent 5.5—Continued.	
Wheat: Bluestem, M. 169	2.8
Do	2.8
Do	3.0
Mean	2.9
Oats: Kherson, G. I. 459	3.3
Do	3.7
Mean	3.5
Oats: Swedish Select	2.6
Do	3.0
Mean	2.8
Barley: Beldi, G. I. 190	2.7
Do	2.7
Mean	2.7
Barley: Hannchen, G. I. 531	2.7
Do	2.8
Do	3.7
Mean	3.1
Rye: Giant Winter	2.8
Do	2.8
Do	3.1
Mean	2.9
Rice: Japan	2.5
Do	3.1
Do	2.6
Mean	2.7
Squash: Yellow Summer Crookneck	2.7
Do	2.5
Mean	2.6
Pea: Canada field, S. P. I. 19389	3.1
Do	3.2
Do	3.7
Mean	3.3
Vetch: Vicia faba, S. P. I. 15428	2.4
Tomato: Livingston's Golden Queen	3.2
Do	3.3
Mean	3.3
Lemon	2.9
Abutilon	2.6
Mean for all determinations, soil No. 8	3.03
Probable error of mean	± .043
Probable error of single observation	± .28
Soil No. 9 (fine sand). Moisture equivalent 6.74.	
Corn: Boone County White, C. I. 119	3.6
Do	3.7
Do	3.8
Mean	3.7

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 9 (fine sand). Moisture equivalent 6.74—Continued.	
Corn: Esperanza, M. 66	3.8
Do	3.6
Do	4.5
Mean	4.0
Sorghum: White durra, S. P. I. 24997	3.1
Do	3.7
Mean	3.4
Sorghum: Dwarf milo, S. P. I. 24970	3.6
Do	3.5
Do	3.8
Mean	3.6
Wheat: Kubanka, G. I. 1440	3.9
Do	3.4
Mean	3.7
Wheat: Bluestem, Minn. 169	3.8
Do	3.4
Mean	3.6
Oats: Kherson, G. I. 459	3.7
Do	3.5
Do	3.7
Mean	3.6
Oats: Swedish Select	3.6
Do	3.8
Mean	3.7
Barley: Beldi, G. I. 190	3.3
Do	3.4
Mean	3.4
Barley: Hannchen, G. I. 531	3.6
Do	3.8
Do	3.8
Mean	3.7
Rye: Giant Winter	3.4
Do	4.1
Do	3.4
Mean	3.6
Rice: Japan	3.5
Do	3.8
Do	3.6
Mean	3.7
Squash: Yellow Summer Crookneck	4.1
Do	3.2
Do	3.8
Mean	3.7
Pea: Canada field, S. P. I. 19389	3.8
Do	3.9
Do	4.2
Mean	4.0
Tomato: Livingston's Golden Queen	3.7
Do	4.1
Do	4.3
Mean	4.0
Soil No. 9 (fine sand). Moisture equivalent 6.74—Continued.	
Abutilon	3.6
Colocasia	4.1
Do	4.9
Do	4.4
Mean	4.5
Mean for all determinations, soil No. 9	3.76
Probable error of mean	± .036
Probable error of single observation	± .23
Soil No. 80 (sandy loam).	
Barley	4.3
Do	3.9
Do	3.8
Mean	4.0
Vetch: Vicia villosa	4.4
Do	4.0
Do	4.4
Do	4.5
Do	5.1
Do	4.1
Do	4.7
Mean	4.5
Probable error of mean	± .09
Probable error of single observation	± .25
Vetch: Vicia faba, S. P. I. 15428	4.5
Pea: Canada field, S. P. I. 19389	3.9
Rape	3.7
Do	4.6
Do	3.5
Mean	3.9
Mean for all determinations, soil No. 80	4.2
Probable error of mean	± .075
Probable error of single observation	± .29
Soil No. 3 (sandy loam). Moisture equivalent 9.7.	
Wheat: Kubanka, G. I. 1440	5.1
Do	4.9
Do	4.9
Do	4.7
Do	5.0
Do	4.7
Do	4.6
Do	4.3
Do	4.6
Do	4.4
Do	4.9
Do	5.4
Mean	4.8
Probable error of mean	± .06
Probable error of single observation	± .21
Sorgo: Red Amber, S. P. I. 17543	4.0
Do	4.6
Mean	4.3
Water cress	4.4
Do	4.9
Do	5.4
Mean	4.9

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 3 (sandy loam). Moisture equivalent 9.7—Continued.	
Mean for all determinations, soil No. 3	4.8
Probable error of mean	± .07
Probable error of single observation	± .27
Soil No. 10 (sandy loam). Moisture equivalent 12.0.	
Corn: Boone County White, C. I. 119	6.4
Do	6.6
Mean	6.5
Corn: Esperanza, M. 66	6.2
Do	6.6
Do	7.0
Mean	6.6
Sorghum: White durra, S. P. I. 24997	6.2
Do	6.1
Do	5.1
Mean	5.8
Sorghum: Dwarf milo, S. P. I. 24970	5.8
Do	5.6
Do	6.4
Mean	5.9
Wheat: Kubanka, G. I. 1440	5.9
Do	6.9
Do	6.1
Mean	6.3
Wheat: Bluestem, Minn. 169	5.7
Do	6.7
Do	6.1
Mean	6.2
Oats: Kherson, G. I. 459	5.9
Oats: Swedish Select	6.2
Do	6.2
Do	6.4
Mean	6.3
Barley: Beldi, G. I. 190	6.9
Do	5.6
Mean	6.3
Barley: Hannchen, G. I. 531	6.1
Do	6.4
Do	5.9
Mean	6.1
Rye: Giant Winter	5.7
Do	5.9
Do	6.0
Mean	5.9
Rice: Japan	5.7
Do	5.1
Do	5.9
Mean	5.6
Squash: Yellow Summer Crookneck	6.2
Do	6.5
Mean	6.4
Soil No. 10 (sandy loam). Moisture equivalent 12.0—Continued.	
Pea: Canada field, S. P. I. 19389	6.9
Do	7.0
Do	6.8
Mean	6.9
Vetch: Vicia faba, S. P. I. 15428	6.5
Do	5.6
Mean	6.1
Tomato: Livingston's Golden Queen	6.9
Tomato: Stone	6.9
Do	6.8
Mean	6.9
Colocasia	7.8
Do	7.9
Do	7.3
Mean	7.7
Mean for all determinations, soil No. 10	6.3
Probable error of mean	± .06
Probable error of single obervation	± .41
Soil No. 82 (sandy loam). Moisture equivalent 14.5.	
Vetch: Vicia villosa	7.9
Vetch: Vicia fulgens, S. P. I. 21502	6.5
Do	7.2
Do	6.8
Mean	6.8
Vetch: Vicia faba, S. P. I. 15428	8.8
Do	7.6
Do	8.2
Mean	8.2
Pea: Canada field, S. P. I. 19389	8.2
Do	8.9
Mean	8.6
Alfalfa: Grimm, S. P. I. 25695	7.8
Mean for all determinations, soil No. 82	7.8
Probable error of mean	± .17
Probable error of single observation	± .54
Soil No. 4 (fine sandy loam). Moisture equivalent 18.1.	
Wheat: Kubanka, G. I. 1440	9.7
Do	9.7
Do	9.9
Do	10.1
Do	9.7
Do	9.8
Do	9.6
Do	9.3
Do	9.4
Do	9.4
Do	9.3
Do	9.3
Do	9.4
Mean	9.6
Probable error of mean	± .05
Probable error of single observation	± .18

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 4 (fine sandy loam). Moisture equivalent 18.1—Continued.	
Wheat: Turkey Red, G. I. 1558	8.8
Do	9.5
Do	9.6
Do	9.8
Do	9.1
Do	9.0
Do	10.0
Do	9.7
Do	8.5
Do	9.6
Do	8.5
Mean	9.3
Probable error of mean	± .12
Probable error of single observation	± .40
Wheat: Bluestem, Minn. 169	8.8
Do	8.9
Do	8.7
Do	9.4
Do	9.6
Do	9.5
Do	9.4
Do	9.0
Do	9.2
Do	7.9
Do	8.0
Do	9.2
Mean	9.0
Probable error of mean	± .11
Probable error of single observation	± .37
Mean for all determinations, soil No. 4	9.3
Probable error of mean	± .06
Probable error of single observation	± .34
Soil No. 26 (sandy loam). Moisture equivalent 18.6.	
Wheat: Kubanka, G. I. 1440	8.9
Do	9.1
Do	9.3
Do	8.8
Do	9.5
Do	8.9
Do	9.4
Do	9.5
Do	9.4
Do	9.0
Do	8.7
Do	9.1
Do	10.0
Do	9.8
Do	9.1
Do	9.3
Do	9.9
Do	9.7
Do	9.1
Do	9.7
Do	7.9
Do	8.3
Do	8.0
Do	8.3
Do	8.1
Do	8.3
Do	8.3
Do	7.8
Do	8.3
Do	8.0
Do	8.5
Do	8.7
Do	8.6
Do	8.6
Do	8.2
Do	8.5
Do	7.8
Soil No. 26 (sandy loam). Moisture equivalent 18.6—Continued.	
Wheat: Kubanka, G. I. 1440	8.0
Do	7.9
Do	7.5
Do	9.9
Do	9.5
Do	9.8
Do	9.5
Do	9.3
Do	9.4
Do	9.6
Do	9.9
Do	9.3
Do	8.9
Do	8.6
Do	9.9
Do	8.3
Do	8.0
Do	7.9
Do	8.8
Do	8.8
Do	8.9
Do	8.7
Do	8.2
Do	7.9
Do	7.8
Mean	8.84
Probable error of mean	± .06
Probable error of single observation	± .47
Vetch: Vicia faba, S. P. I. 15428	9.7
Do	8.9
Mean	9.3
Mean for all determinations, soil No. 26	8.84
Probable error of mean	± .06
Probable error of single observation	± .46
Soil No. 12 (loam). Moisture equivalent 18.9.	
Corn: Boone County White, C. I. 119	9.6
Do	10.0
Do	10.1
Mean	9.9
Corn: Esperanza, M. 66	10.1
Do	11.0
Mean	10.6
Sorghum: White durra, S. P. I. 24997	9.5
Do	9.3
Do	9.7
Mean	9.5
Sorghum: Dwarf milo, S. P. I. 24970	10.8
Do	9.4
Do	9.9
Mean	10.0
Wheat: Kubanka, G. I. 1440	9.4
Do	10.0
Do	11.4
Mean	10.3
Wheat: Bluestem, Minn. 169	10.1
Do	9.9
Do	10.1
Mean	10.0

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 12 (loam). Moisture equivalent 18.9—Continued.	
Oats: Kherson, G. I. 459	10.5
Do	11.2
Do	11.5
Mean	11.1
Oats: Swedish Select	9.8
Do	10.0
Mean	9.9
Barley: Beldi, G. I. 190	10.8
Do	11.1
Do	11.0
Mean	11.0
Barley: Hannchen, G. I. 531	10.3
Do	9.2
Do	10.4
Mean	10.0
Rye: Giant Winter	9.5
Do	9.7
Mean	9.6
Rice: Japan	8.6
Do	11.6
Mean	10.1
Squash: Yellow Summer Crookneck	9.3
Do	9.5
Mean	9.4
Pea: Canada field, S. P. I. 19389	12.7
Do	12.0
Mean	12.4
Vetch: Vicia faba, S. P. I. 15428	10.5
Do	9.4
Do	9.2
Mean	9.7
Tomato: Livingston's Golden Queen	12.0
Do	11.5
Do	11.6
Mean	11.7
Clover, red	10.7
Colocasia	12.7
Do	11.4
Mean	12.1
Mean for all determinations, soil No. 12	10.4
Probable error of mean	± .10
Probable error of single observation	± .65
Soil No. 78 (loam). Moisture equivalent 23.8.	
Wheat: Kubanka, G. I. 1440	12.3
Do	13.8
Do	11.2
Mean	12.4
Barley	11.6
Do	11.4
Do	13.7

Soil and species or variety of plant.	Coefficient.
Soil No. 78 (loam). Moisture equivalent 23.8—Continued.	
Barley	14.2
Do	12.2
Do	13.1
Do	11.8
Do	12.5
Do	11.3
Do	11.7
Do	13.4
Do	13.2
Do	12.4
Mean	12.5
Probable error of mean	± .25
Probable error of single observation	± .89
Vetch: Vicia villosa	14.1
Do	13.4
Do	12.5
Do	12.3
Do	14.0
Do	12.9
Do	13.1
Mean	13.2
Probable error of mean	± .18
Probable error of single observation	± .48
Vetch: Vicia fulgens, S. P. I. 21502	12.9
Do	12.1
Do	12.5
Mean	12.5
Vetch: Vicia faba, S. P. I. 15428	14.2
Do	14.6
Do	12.7
Mean	13.8
Alfalfa: Grimm, S. P. I. 25695	13.4
Do	12.3
Mean	12.9
Rape	12.6
Do	11.2
Do	12.1
Mean	12.0
Mean for all determinations, soil No. 78	12.7
Probable error of mean	± .18
Probable error of single observation	± .63
Soil No. 86 (clay loam). Moisture equivalent 23.3.	
Cucumber: Nichol's Medium Green	12.1
Muskmelon: Extra Early Hackensack	13.9
Barley: Hull-less	12.2
Corn: Boone County White, C. I. 119	13.6
Corn: Esperanza, M. 66	14.2
Corn: Northwestern Dent	14.2
Corn: Mexican June	12.2
Corn: Chico, M. 72	14.3
Mean for all determinations, soil No. 86	13.4
Probable error of mean	± .22
Probable error of single observation	± .65
Soil No. 5 (loam). Moisture equivalent 25.0.	
Wheat: Kubanka, G. I. 1440	14.1
Do	14.7
Do	14.3

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 5 (loam). Moisture equivalent 25.0—Continued.	
Wheat: Kubanka, G. I. 1440	14.7
Do	13.4
Do	14.6
Do	13.1
Do	13.5
Do	13.7
Do	14.0
Do	13.7
Do	13.4
Do	14.0
Mean for all determinations, soil No. 5	13.9
Probable error of mean	± .10
Probable error of single observation	± .36
Soil No. 13 (clay loam). Moisture equivalent 27.4.	
Corn: Boone County White, C. I. 119	15.7
Do	16.5
Do	14.3
Mean	15.5
Corn: Esperanza, M. 66	14.7
Do	15.9
Do	16.0
Mean	15.5
Sorghum: White durra, S. P. I. 24997	14.4
Do	13.5
Do	13.6
Mean	13.8
Sorghum: Dwarf milo, S. P. I. 24970	14.3
Do	14 0
Do	14.3
Mean	14.1
Wheat: Kubanka, G. I. 1440	14.8
Do	14.2
Do	15.0
Do	14.1
Mean	14.5
Wheat: Bluestem, Minn. 169	14.2
Do	14.4
Do	14.2
Mean	14.3
Oats: Kherson, G. I. 459	16.0
Do	14.9
Do	13.5
Mean	14.8
Oats: Swedish Select	15.0
Do	15.4
Do	14.9
Mean	15.1
Barley: Beldi, G. I. 190	14.2
Do	14.5
Do	13.8
Mean	14.2
Barley: Hannchen, G. I. 531	14.7
Do	13.9
Do	13.7
Mean	14.1
Soil No. 13 (clay loam). Moisture equivalent 27.4—Continued.	
Rye: Giant Winter	14.6
Do	14.3
Do	14.4
Mean	14.4
Rice: Japan	12.9
Do	13.1
Mean	13.0
Squash: Yellow Summer Crookneck	15.8
Do	14.7
Do	14.7
Mean	15.1
Pea: Canada field, S. P. I. 19389	17.9
Do	15.2
Do	16.8
Mean	16.6
Vetch: Vicia faba, S. P. I. 15428	16.0
Do	14.0
Do	14.2
Mean	14.7
Tomato: Livingston's Golden Queen	15.4
Do	15.5
Do	15.1
Mean	15.3
Citrus	15.7
Abutilon	14.5
Do	14.2
Mean	14.4
Colocasia	17.5
Do	17.1
Mean	17.3
Ranunculus septentrionalis	15.0
Do	14.1
Mean	14.6
Mean for all determinations, soil No. 13	14.8
Probable error of mean	± .10
Probable error of single observation	± .76
Soil No. 14 (clay loam). Moisture equivalent 29.3.	
Corn: Boone County White, C. I. 119	17.0
Do	17.7
Do	15.5
Do	17.6
Do	17.9
Do	17.1
Do	17.8
Do	17.2
Do	15.7
Do	15.9
Do	17.0
Do	16.3
Do	17.5
Do	17.2
Do	16.7
Mean	17.0
Probable error of mean	± .13
Probable error of single observation	± .52

TABLE XI.—*Wilting coefficients of various soils for different plants*—Continued.

Soil and species or variety of plant.	Coefficient.
Soil No. 14 (clay loam). Moisture equivalent 29.3—Continued.	
Tomato: Livingston's Golden Queen	16.5
Do	16.5
Do	16.2
Mean	16.4
Squash: Yellow Summer Crookneck	16.6
Wheat: Kubanka, G. I. 1440	17.3
Do	17.3
Do	17.8
Do	18.3
Do	15.4
Do	16.5
Do	17.8
Do	17.4
Do	17.4
Do	16.0
Mean	17.1
Probable error of mean	± .22
Probable error of single observation	± .68
Corn: Hopi, M. 7	16.4
Buckwheat: Orenberg	17.9
Pachyphytum aduncum	17.7
Echeveria pubescens	18.8
Nopalea cochenelifera	17.6
Soil No. 14 (clay loam). Moisture equivalent 29.3—Continued.	
Mean for all determinations, soil No. 14	17.1
Probable error of mean	± .10
Probable error of single observation	± .56
Soil No. 6 (clay loam). Moisture equivalent 30.2.	
Wheat: Kubanka, G. I. 1440	16.3
Do	16.9
Do	16.8
Do	16.4
Do	15.5
Do	15.7
Do	17.3
Do	15.6
Do	16.0
Do	16.0
Do	16.2
Do	16.3
Do	16.7
Do	16.2
Do	16.3
Do	16.7
Mean for all determinations, soil No. 6	16.3
Probable error of mean	± .08
Probable error of single observation	± .33

RELATIVE INFLUENCE OF THE SOIL AND THE PLANT ON THE WILTING COEFFICIENT.

An inspection of the results given in Table XI makes the great influence of the soil texture upon the wilting coefficient at once apparent. The mean wilting coefficient of the different soils used ranges from less than 1 per cent to over 16 per cent. The range is even greater for extreme types of soil, as we shall show later, the wilting coefficient of the heaviest clays being as high as 30 per cent. In other words, the moisture content of the heaviest clay soils when reduced to the point where plants wilt is more than 30 times as great as in dune sands under similar conditions. Plants will wilt in the heaviest clay soils when the water content is greater than sand soils can possibly hold if drainage is provided. It is thus seen that the great differences in the wilting coefficient encountered as we go from soil type to soil type are due simply to the difference in the moisture retentiveness of the soils.

On the other hand, the results given in Table XI show that the use of different plants as indicators of the wilting point produces only a relatively small change in the wilting coefficient of a given soil. Representing the mean value of the wilting coefficient of a given soil by 100, a range from 95 to 105, approximately, would result from the use of different plants as indicators. The influence of the

differences exhibited in plants on the wilting coefficient is, then, very small as compared with the differences in the moisture retentiveness of soils, the maximum values for plants being only about 10 per cent greater than the minimum values, as compared with 3,000 per cent in the case of extreme soil types.

Slight differences in plants do, however, exist, and these differences as a rule hold for the different plants throughout the determinations with the several soils employed. In order to make a more extended comparison possible, all of the determinations which have been made with a given plant have been brought together and reduced in such a manner that the collected results for the different plants can be directly compared. These results are given in the following section.

RELATIVE WILTING COEFFICIENTS FOR DIFFERENT PLANTS.

In making a final comparison of the relative ability of plants to reduce the soil moisture before wilting it is necessary, when different soils are used, to eliminate from the results the effect of the moisture retentiveness of the particular soil used and thus reduce the determinations for all the soils to a uniform basis for comparison. This reduction has been accomplished by determining the ratio of each individual determination to the mean of the whole series of determinations made upon a particular soil, as given at the end of each table. In other words, each determination is divided by the mean of all the determinations for that soil, irrespective of the kind of plant used as an indicator. If, then, the wilting coefficient of a soil for a particular plant is higher than the average, the ratio of the individual determinations for that plant to the mean of the series will be greater than unity. If, on the other hand, a plant is capable of reducing the moisture content of a particular soil somewhat below the point attained by the other varieties of plants grown in that soil, then the ratio of the individual determinations for this plant to the mean of the whole series will be less than unity. With the aid of these ratios, then, it is possible to determine for any individual plant, no matter in what soil it may be grown, the extent to which it is able to reduce the soil-moisture content below the point reached by other plants before wilting occurs.

The determinations in Table XI, together with those in Table XIII, have been reduced in this way, and the results are presented in Table XII, which contains under each crop and variety the total number of wilting-coefficient determinations made with that variety and the mean of all the individual ratios for that variety calculated as described above. When the number of observations were sufficient to justify the calculation of the probable error, such calculation is also given.

Referring to Table XII it will be seen that the corn varieties, taken as a group, give a ratio which is slightly greater than unity. In other words, corn appears to give a slightly higher wilting coefficient than the mean of all the plants used. The several varieties of corn differed only slightly, the lowest ratio being given by Boone County White, a variety largely grown in humid regions. It is of interest to note that the Mexican and Indian varieties native to dry regions gave no indication of being able to reduce the soil-moisture content lower than other varieties.

It will be seen that in the sorghum group also the differences exhibited by the several varieties tested are small. The two varieties which gave the lowest value were White durra and Red Amber, each having a mean ratio of 0.94, indicating that they are capable of reducing the soil-moisture content somewhat below that reached by corn at the time of wilting.

The results obtained with different varieties of the small-grain crops—millet, wheat, oats, and barley—show that the influence of the different varieties upon the wilting coefficient is slight, the extreme range[1] for the four crops being from 0.95 to 1.03. Rye, of which only one variety was tested, gave a wilting coefficient slightly lower than the other grains and comparable with the sorghums.

Of special interest are the low determinations observed in the case of rice, in view of the fact that this crop is generally supplied with an abundance of water. The low wilting coefficient is probably due to the abundant development of fine fibrous roots, which insures a root penetration through all parts of the soil.

The different grasses tested, most of which are natives of the Great Plains, gave ratios differing only slightly from one another and in practical agreement with the small grains. Most of the legumes, on the other hand, gave a mean wilting coefficient slightly higher than the average.

The miscellaneous plants upon which only a few determinations have been made are grouped in the last part of the tables as hydrophytes, mesophytes, and xerophytes. The water plants give a mean wilting coefficient slightly higher than the other groups, due to the presence in this group of Isoetes, submerged plants of which were taken from the water and grown in the air without being permitted to develop new leaves. This plant also had a poor root distribution. If we except Isoetes, the other hydrophytes give a mean wilting coefficient identical with that of the mesophytes. The xerophytes tested gave a mean ratio intermediate between the hydrophytes and mesophytes. This would indicate that plants native to dry regions are unable to reduce the water content of the soil to a lower point at the time of wilting than is reached by other plants.

[1] Based upon all variety tests which include six or more determinations.

TABLE XII.—*Observations showing the relative wilting coefficients for different varieties.*

Plant and species or variety.	Number of observations.	Mean ratio.	Probable error— Of mean ratio.	Probable error— Of single ratio.
Corn:				
Boone County White, U. S. S. 119	33	1.00	0.007	0.038
Esperanza, M. 66	16	1.06	.013	.052
Minn. 13, U. S. S. 133	3	1.03		
Hopi, A. 7	3	1.05		
U. S. S. 165	4	1.00		
Indian Flint	3	1.08		
Northwestern Dent	4	1.09		
Laguna	4	1.05		
Chico, M. 72	2	1.06		
Iowa Silvermine	3	1.06		
Chinese, S. P. I. 22308	3	1.03		
Sorghum:				
White durra, S. P. I. 24997	17	.94	.012	.052
Dwarf milo, S. P. I. 24970	17	.994	.017	.072
Red Amber, S. P. I. 17543	7	.94	.007	.044
Black Amber, Minn. 341	12	1.00	.026	.089
Red Kafir, S. P. I. 24985	3	1.01		
Blackhull Kafir, S. P. I. 24975	3	1.03		
Dagdi durra, S. P. I. 9856	3	1.02		
Blackhull kowliang, G. I. 310	3	1.03		
Brown kowliang, S. P. I. 24993	1	1.04		
Millet:				
Kursk, S. P. I. 22420	27	.954	.008	.040
Common, S. P. I. 22423	6	.96	.011	.027
Siberian, S. P. I. 21076	6	1.01	.009	.023
German, S. P. I. 26845	3	1.00		
Chaetochloa italica, S. P. I. 21073	3	1.04		
Proso, G. I. 72	3	.99		
Wheat:				
Kubanka, G. I. 1440	593	1.00	.0021	.051
Bluestem, Minn. 169	28	.96	.0066	.035
Turkey Red, G. I. 1558	11	.99	.0116	.038
Fretes, S. P. I. 19239	3	.94		
Kubanka, G. I. 1354	3	.94		
Kubanka, G. I. 2246	3	.97		
Yellow Gharnovka, S. P. I. 26008	3	.94		
Yellow Gharnovka, G. I. 1444	3	.96		
Power's Fife, G. I. 3025	3	.95		
Pelissier, G. I. 1584	3	.97		
Emmer, S. P. I. 19907	3	1.07		
Oats:				
Kherson, G. I. 459	15	1.03	.0149	.058
Swedish Select, S. P. I. 24877	13	.984	.009	.033
Canadian, S. P. I. 12880	3	.96		
Seventy-five Day, G. I. 337	3	1.02		
Sixty-Day, G. I. 639	3	1.04		
Big Four, G. I. 558	3	1.03		
Burt, S. P. I. 24670	3	.93		
Red Rustproof, G. I. 458	3	.92		
Barley:				
Beldi, G. I. 190	14	.97	.013	.054
Hannchen, G. I. 531	18	.98	.011	.047
Unknown	16	.98	.013	.034
Mariut, G. I. 261	3	.95		
Telli, G. I. 194	3	.92		
White Smyrna, G. I. 195	3	.94		
Oderbrucker, S. P. I. 26105	2	.92		
Hull-less, S. P. I. 12709	1	.91		
Rye, Giant Winter	19	.94	.011	.049
Rice:				
Japan, G. I. 1642	15	.92	.014	.054
Carolina Gold, G. I. 1645	3	.96		
Honduras, G. I. 1643	3	1.03		
Grasses:				
Bromus inermis	33	.94	.005	.028
Agropyron smithii	11	1.03	.013	.043
Agropyron tenerum	15	.99	.013	.052
Agropyron cristatum	6	.96	.013	.032
Elymus canadensis	3	1.00		
Stipa vaseyi	3	.99		
Sitanion hystrix	3	.97		
Aristida longiseta	2	1.00		
Bouteloua oligostachya	1	1.01		
Legumes:				
Alfalfa, Grimm, S. P. I. 25695	33	.98	.006	.035
Canada field pea, S. P. I. 19389	28	1.05	.012	.064

TABLE XII.—*Observations showing the relative wilting coefficients for different varieties*—Continued.

Plant and species or variety.	Number of observations.	Mean ratio.	Probable error— Of mean ratio.	Probable error— Of single ratio.
Legumes—Continued.				
Melilotus alba, S. P. I. 21216	8	1.03	0.012	0.033
Vicia villosa,	17	1.04	.013	.053
Vicia faba, S. P. I. 15428	23	1.02	.016	.078
Vicia fulgens, S. P. I. 21502	6	.93	.....	.....
Vicia atrapurpurea, S. P. I. 18132	3	1.05	.....	.....
Vicia ervilia, S. P. I. 16137	3	.92	.....	.....
Chick-pea, S. P. I. 24322	3	.93	.....	.....
Cowpea, S. P. I. 26497	3	.98	.....	.....
Clover, red	5	1.04	.....	.....
Sanfoin, S. P. I. 24931	3	1.00	.....	.....
Lupinus pusillus	2	.97	.....	.....
Cucurbits:				
Squash	15	1.01	.018	.073
Cucumber	1	.90	.....	.....
Muskmelon	1	1.04	.....	.....
Tomato:				
Livingston's Golden Queen	17	1.05	.011	.043
Stone	3	1.08	.....	.....
Colocasia, S. P. I. 21190	19	1.13	.015	.056
Hydrophytes:				
Water cress	3	1.03	.....	.....
Isoetes saccharata	2	1.33	.....	.....
Juncus balticus	1	1.07	.....	.....
Ranunculus septentrionalis	2	.98	.....	.....
Mesophytes:				
Morning-glory	3	1.11	.....	.....
Plantago	2	1.06	.....	.....
Citrus limonum	1	.96	.....	.....
Abutilon	2	.91	.....	.....
Cotton	2	1.05	.....	.....
Coleus	5	.99	.....	.....
Lettuce	3	1.11	.....	.....
Potato	3	1.06	.....	.....
Buckwheat	1	1.05	.....	.....
Sugar beet	3	1.06	.....	.....
Flax	2	.99	.....	.....
Rape	3	.94	.....	.....
Amaranthus retroflexus	5	1.01	.....	.....
Xerophytes:				
Grindelia squarrosa	4	1.08	.....	.....
Vernonia marginata	3	1.04	.....	.....
Artemisia gnaphalodes	6	1.06	.....	.....
Pachyphytum aduncum	1	1.03	.....	.....
Echeveria pubescens	1	1.10	.....	.....
Nopalea cochenelifera	1	1.03	.....	.....
Total number of observations	1,318	.....	.....	.....
Weighted mean	.....	1.00	.....	.054

SUMMARY OF RESULTS FOR DIFFERENT CROPS.

Corn	75	1.03	0.003	0.042
Sorghum	66	.98	.008	.062
Millet	48	.97	.006	.035
Wheat	653	.994	.002	.049
Oats	46	.995	.007	.047
Barley	60	.97	.006	.047
Rye	19	.94	.011	.049
Rice	21	.94	.012	.054
Grasses	77	.97	.005	.040
Legumes	138	1.01	.005	.059
Cucurbits	17	.99	.016	.068
Tomato	20	1.06	.009	.040
Colocasia	19	1.13	.005	.066
Hydrophytes	8	1.10	.037	.105
Mesophytes	35	1.02	.010	.058
Xerophytes	16	1.06	.008	.032
Total number of observations	1,318	.....	.....	.....
Weighted mean	.....	1.00	.....	.....

Looking at the results given in Table XII as a whole, it is seen that the relative wilting coefficients of the different species range from 0.92 for Japan rice to 1.13 for Colocasia.[1] The Colocasia is an extremely coarse-rooted plant, and the fine fibrous roots that are so characteristic of the root systems of many of the grasses are here wholly absent. The result is that the Colocasia fails to reduce the water content of the soil uniformly. From those parts of the soil mass which are located some distance from the roots water can be obtained only by capillary action, and this adjustment takes place very slowly in the soil when the water content is approaching the wilting coefficient. The determination of the moisture content of the whole soil mass at the time of wilting consequently gives too high a value for the wilting coefficient. If the Colocasia is excluded on account of its imperfect root distribution, the upper limit of the relative wilting coefficient drops to 1.06.

Imperfect root distribution is again encountered, to a less degree, in corn, certain of the legumes, and some of the coarse-rooted plants of the Great Plains. Coarse-root systems as a rule are accompanied by high values for the wilting coefficient, and such values are to be attributed to imperfect root distribution rather than to any inherent inability of the plant to reduce the soil moisture content to the point reached by other plants.

The results of the determinations shown in Table XII are summarized at the end of the table with regard to crops without reference to varieties. Reference to the mean ratios shows the slight difference that exists among the various crops with respect to their ability to reduce the soil-moisture content before wilting occurs. Sorghum, millet, wheat, oats, barley, and the grasses are practically the same. Rye and rice appear to be a little lower, while corn and the legumes are slightly higher.

In a soil whose mean wilting coefficient for all plants is 10 per cent, corn, according to the above figures, would wilt with a soil-moisture content of 10.3 per cent, while sorghum would wilt with a moisture content of 9.8. Assuming that the roots were distributed to a depth of 4 feet, this would correspond to an additional amount of water for the sorghum plants in the 4 feet of soil equivalent to a rain of 0.3 of an inch, all of which penetrated to the root zone. It is possible that conditions might arise whereby the sorghum would be able to profit from this slight additional supply of moisture, but such a limited reserve would scarcely suffice to ameliorate conditions during a drought to any greater extent than would a single cool, cloudy day.

[1] This statement applies to all varieties upon which six or more determinations were made. The mean of a less number of determinations than six can only be considered as indicating whether the wilting coefficient for that plant is above or below normal. Ten or more determinations are essential for a quantitative expression to which weight can be attached.

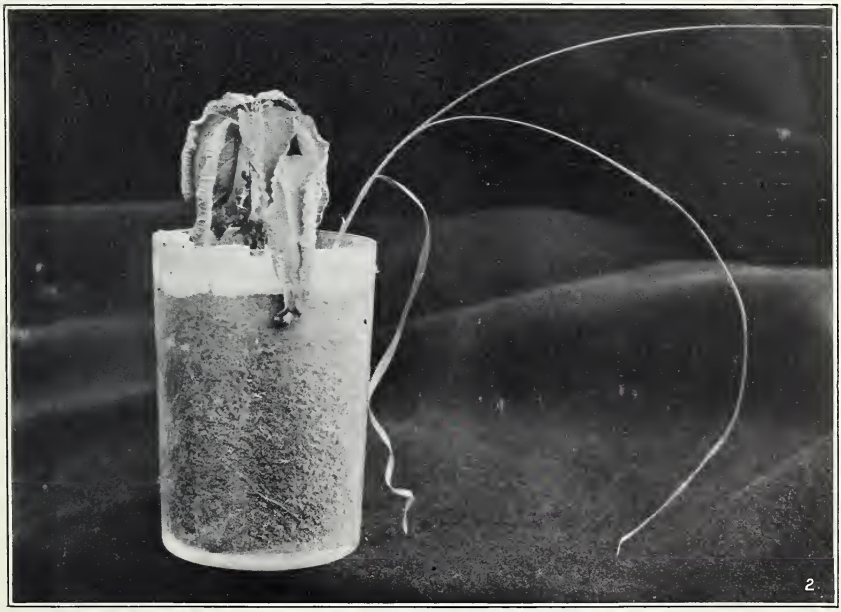

FIG. 1.—AT THE LEFT: BOONE COUNTY WHITE CORN, KUBANKA WHEAT 1440, AND JUNCUS BALTICUS. AT THE RIGHT: EARLY ROSE POTATO AND KUBANKA WHEAT 1440. FIG. 2.—COLEUS AND KUBANKA WHEAT 1440.

THE SIMULTANEOUS WILTING OF PLANTS GROWING IN THE SAME SOIL MASS.

COMPARISON OF THE WILTING COEFFICIENT FOR DIFFERENT PLANTS BY GROWING THEM SIMULTANEOUSLY IN THE SAME POT.

In addition to the determinations given in the preceding tables, pot cultures have been made of a large number of different plants with Kubanka wheat growing simultaneously in each pot (Tables XIII and XIV). This procedure renders it possible to make a direct comparison of the relative wilting point of the two plants independent of any determination of soil moisture (Pl. II). It also tends to eliminate any disturbances arising from environmental conditions. Differences due to unequal root distribution, however, enter here as in the other determinations. The results are given in Table XIII, which shows the relative time of wilting of the two plants under comparison. Soil-moisture determinations were also made in connection with these cultures at the time of wilting, as in the preceding series.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat.*

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Corn:			
U. S. S. 133	10.1		
Do	9.9		
Do	9.8	9.9	Wilted simultaneously; corn shows more discoloration.
Hopi, A. 7	10.5		
Do	9.9		
Do	10.0	10.1	Wilted simultaneously.
Triple Hybrid, U. S. S. 165	10.0		
Do	9.9		
Do	9.4	9.8	Do.
Indian Flint	10.9		
Do	10.2		
Do	10.4	10.5	Do.
Northwestern Dent	10.2		
Do	10.4		
Do	11.3	10.6	Wilted simultaneously; corn shows more discoloration.
Laguna	10.5		
Do	10.1		
Do	11.0	10.5	Wilted simultaneously.
Chico, M. 72	10.0	10.0	
Iowa Silvermine	10.2		
Do	10.2		
Do	10.3	10.2	Do.
Chinese, S. P. I. 22308	9.7		
Do	9.8		
Do	10.1	9.9	Do.
Sorghum:			
Black Amber, Minn. 341	10.1		
Do	9.7		
Do	10.7		
Do	10.4		
Do	10.3		
Do	11.2		
Do	10.6		

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Sorghum—Continued.			
Black Amber, Minn. 341	9.3		
Do	9.8	10.2	Wilted simultaneously; sorghum turns light color and leaves do not roll as much as wheat.
Red kafir, S. P. I. 24985	10.2		
Do	9.4		
Do	9.6	9.7	Do.
Black-hull kafir, S. P. I. 24975	9.7		
Do	10.0		
Do	9.9	9.9	Wilted simultaneously.
Dadgi durra, S. P. I. 9856	10.0		
Do	9.5		
Do	10.0	9.8	Do.
Black-hull kowliang, G. I. 310	9.6		
Do	10.1		
Do	10.0	9.9	Do.
Brown kowliang, S. P. I. 24993	10.0	10.0	Do.
Millet:			
Kursk, S. P. I. 22420	8.7		
Do	8.6		
Do	9.1		
Do	8.6		
Do	9.0		
Do	9.3		
Do	9.0		
Do	9.8		
Do	9.5		
Do	9.1		
Do	8.6		
Do	8.9		
Do	8.7		
Do	9.1		
Do	8.7		
Do	10.1		
Do	10.3		
Do	9.8		
Do	9.6		
Do	10.1		
Do	10.2		
Do	9.3		
Do	9.0		
Do	9.6		
Do	8.2		
Do	8.9		
Do	8.9	9.5	Do.
Common, S. P. I. 22423	9.0		
Do	9.3		
Do	9.1		
Do	9.1		
Do	9.3		
Do	10.0	9.3	Do.
Chaetochloa italica, S. P. I. 21073	9.6		
Do	10.6		
Do	10.0	9.7	Do.
Proso, G. I. 72	9.3		
Do	9.8		
Do	9.6	9.6	Do.
Siberian, S. P. I. 21076	9.4		
Do	9.3		
Do	9.8		
Do	9.7		
Do	10.1		
Do	9.8	9.7	Do.
German, S. P. I. 26845	9.7		
Do	9.4		
Do	9.7	9.6	Do.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Wheat:			
Kubanka,[1] G. I. 1440	9.1		
Do	9.8		
Do	8.5		
Do	7.8		
Do	9.9		
Do	9.0		
Do	8.6		
Do	9.8		
Do	9.4		
Do	9.0		
Do	9.7		
Do	9.8		
Do	9.6		
Do	11.1		
Do	8.9		
Do	9.7		
Do	9.5		
Do	9.4		
Do	9.6		
Do	9.7		
Do	9.6		
Do	8.9		
Do	9.6		
Do	9.4		
Do	9.9		
Do	10.7		
Do	10.2		
Do	8.8		
Do	8.1		
Do	8.4		
Do	9.3		
Do	10.1		
Do	9.0		
Do	9.3		
Do	9.2		
Do	9.6		
Do	11.4		
Do	9.0		
Do	9.4		
Do	11.4		
Do	11.7		
Do	10.2		
Do	8.8		
Do	9.3		
Do	9.1		
Do	9.2		
Do	9.0		
Do	8.2		
Do	9.1		
Do	8.9		
Do	9.0		
Do	10.0		
Do	10.7		
Do	10.0		
Do	10.2		
Do	10.2		
Do	10.0		
Do	10.0		
Do	9.6		
Do	9.1		
Do	9.2		
Do	9.6		
Do	11.0		
Do	10.7		
Do	8.4		
Do	11.1		
Do	9.9		
Do	11.0	9.3	
Fretes, S. P. I. 19239	9.1		
Do	9.2		
Do	8.9	9.1	Wilted simultaneously.

[1] Only Kubanka, G. I. 1440, in these pots.

TABLE XIII—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture eqvivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Wheat—Continued:			
Kubanka, G. I. 1354	9.2		
Do	8.9		
Do	9.3	9.1	Wilted simultaneously.
Kubanka, G. I. 2246	9.4		
Do	9.3		
Do	9.4	9.4	Do.
Yellow Gharnovka, S. P. I. 26008	7.8		
Do	9.5		
Do	9.9	9.1	Do.
Yellow Gharnovka, G. I. 1444	9.4		
Do	9.5		
Do	8.9	9.3	Do.
Power's Fife	9.2		
Do	9.3		
Do	9.2	9.2	Do.
Pelissier, G. I. 1584	8.7		
Do	9.3		
Do	10.0	9.3	Do.
Oats:			
Canadian	8.5		
Do	9.7		
Do	9.0	9.1	Do.
Seventy-five Day, G. I. 337	10.0		
Do	9.6		
Do	9.9	9.8	Do.
Sixty-Day, G. I. 639	9.6		
Do	9.8		
Do	10.7	10.0	Do.
Big Four	10.0		
Do	9.9		
Do	9.7	9.9	Do.
Burt	9.0		
Do	9.2		
Do	8.9	9.1	Do.
Red Rustproof	8.9		
Do	8.8		
Do	9.0	8.9	Do.
Barley:			
Mariut, G. I. 261	8.8		
Do	8.7		
Do	10.0	9.2	Do.
Telli, G. I. 194	9.2		
Do	8.7		
Do	8.8	8.9	Wilted simultaneously. Old leaves of barley do not roll.
White Smyrna, G. I. 195	9.0		
Do	9.4		
Do	8.9	9.1	Do.
Oderbrucker, S. P. I. 26105	9.1		
Do	8.6	8.9	Wilted simultaneously.
Rice:			
Carolina Gold, G. I. 1645	9.2		
Do	9.5		
Do	9.3	9.3	Do.
Honduras, G. I. 1643	10.1		
Do	10.2		
Do	9.5	9.9	Do.
Emmer	10.2		
Do	11.3		
Do	9.9	10.5	Wilted simultaneously. Emmer rolls more than wheat; could not recover in damp chamber.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Grasses:			
Agropyron tenerum	8.7		
Do	9.6		
Do	9.6		
Do	10.4		
Do	9.7		
Do	10.9		
Do	10.3		
Do	10.5		
Do	8.8		
Do	8.4		
Do	9.3		
Do	9.0		
Do	9.3		
Do	9.7		
Do	9.0	9.5	Wilted simultaneously.
A. cristatum	9.9		
Do	9.2		
Do	9.6		
Do	9.2		
Do	8.9		
Do	8.7	9.3	Do.
A. smithii	10.1		
Do	9.6		
Do	10.2		
Do	9.8		
Do	9.5		
Do	9.4		
Do	10.6		
Do	10.7		
Do	9.7		
Do	9.7		
Do	11.4	10.1	Do.
Bromus inermis	9.4		
Do	8.8		
Do	9.6		
Do	10.2		
Do	9.5		
Do	9.5		
Do	9.7		
Do	8.9		
Do	9.5		
Do	9.3		
Do	8.6		
Do	9.0		
Do	9.5		
Do	9.5		
Do	9.1		
Do	8.9		
Do	9.5		
Do	9.1		
Do	8.9		
Do	10.1		
Do	9.5		
Do	10.3		
Do	9.3		
Do	9.0		
Do	9.3		
Do	9.0		
Do	9.3		
Do	9.6		
Do	9.4		
Do	9.5		
Do	9.9		
Do	10.1		
Do	9.8	9.4	Do.
Elymus canadensis	9.6		
Do	9.7		
Do	9.6	9.6	Do.
Stipa vaseyi	9.3		
Do	9.6		
Do	9.7	9.5	Do.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Grasses—Continued.			
Sitanion hystrix	9.2		
Do	9.6		
Do	9.3	9.4	Wilted simultaneously.
Aristida longiseta	9.5		
Do	9.7	9.6	Do.
Bouteloua oligostachya	9.7		
Alfalfa:			
Grimm, S. P. I. 25695	9.2		
Do	9.4		
Do	9.0		
Do	9.0		
Do	8.9		
Do	9.0		
Do	9.2		
Do	9.3		
Do	9.7		
Do	8.9		
Do	8.8		
Do	9.7		
Do	9.0		
Do	9.3		
Do	8.9		
Do	10.0		
Do	9.1		
Do	9.2		
Do	8.7		
Do	9.2		
Do	9.6		
Do	9.0		
Do	9.8		
Do	10.3		
Do	10.1		
Do	10.4		
Do	10.0		
Do	9.8		
Do	10.1		
Do	9.6	9.4	Do.
Vetch:			
Vicia faba, S. P. I. 15428	11.0	11.0	Do.
Vicia atropurpurea, S. P. I. 18132	10.2		
Do	10.1		
Do	10.4		
Do	9.9	10.2	Wilted simultaneously. Vicia does not look badly wilted, but could not recover in damp chamber.
Vicia ervilia	8.9		
Do	9.1		
Do	8.7	8.9	Wilted simultaneously. Leaves wilt, but remain upright.
Melilotus alba, S. P. I. 21216	10.3		
Do	10.6		
Do	10.2		
Do	9.6		
Do	9.9		
Do	10.4		
Do	9.1		
Do	10.1	10.0	Wilted simultaneously.
Canada field pea, S. P. I. 19389	10.2		
Do	9.3		
Do	9.4		
Do	9.9	9.8	Wilted simultaneously. Lower leaves of pea wilt first.
Cowpea, S. P. I. 26497	8.9		
Do	9.6		
Do	9.9	9.5	Wilted simultaneously.
Chick-pea	10.1		
Do	8.5		
Do	8.2	8.9	Wilted simultaneously. Could not recover in damp chamber. Chick-pea leaves do not droop; they merely fold together.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Sanfoin, S. P. I. 24931	9.0		
Do	10.1		
Do	9.1	9.4	Wilted simultaneously.
Clover, red	10.5		
Do	10.4		
Do	10.7	10.5	Do.
Lupinus pusillus	9.3		
Do	9.4	9.4	Do.
Morning-glory	10.5		
Do	10.8		
Do	10.7	10.7	Do.
Cotton: Columbia	9.8		
Do	10.3	10.1	Do.
Adiantum pedatum	11.0	11.0	Do.
Juncus balticus	10.3	10.3	Wheat wilted and leaves of rush dying back simultaneously. Corn in same pot wilting at the same time. No recovery in damp chamber.
Salix sp	8.8		
Do	8.1		
Do	8.4	8.4	Wilted simultaneously. Pots allowed to stand too long before moisture determinations were made.
Plantago major	10.5		
Do	9.8	10.2	Wilted simultaneously.
Lettuce	10.9		
Do	10.5		
Do	10.8	10.7	Do.
Colocasia	10.3		
Do	11.2		
Do	10.1		
Do	10.1		
Do	10.1		
Do	10.0	10.3	Wilted simultaneously. No evidence of difference. Colocasia has poor root distribution. Neither wheat nor colocasia recovered in damp chamber.
Isoetes saccharata	13.1		
Do	12.7	12.9	Submerged plants transplanted and kept in glass damp chamber. Outer leaves dying (do not wilt) simultaneously with the wilting of the wheat plants. Poor root distribution of both wheat and Isoetes.
Oak: Chestnut	11.0	11.0	Wilted simultaneously. Poor root distribution.
Beet, sugar	10.7		
Do	9.4		
Do	10.6	10.2	Wilted simultaneously.
Flax	9.3		
Do	9.8	9.6	Do.
Potato:			
Early Rose	11.0		
Do	10.5		
Do	9.3	10.3	Do.
Coleus	9.0		
Do	9.5		
Do	8.4		
Do	10.3		
Do	10.7	9.6	Do.
Grindelia squarrosa	10.0		
Do	11.2		
Do	10.4		
Do	9.9	10.4	Do.

TABLE XIII.—*Wilting-coefficient determinations in soil No. 30 (fine sandy loam), moisture equivalent 18.5, for different plants grown simultaneously in the same pot with Kubanka wheat*—Continued.

Plant species or variety.	Coefficient.	Mean.	Comparison with Kubanka wheat.
Amaranthus retroflexus	9.1		
Do	9.7		
Do	11.0		
Do	9.4		
Do	9.6	9.8	Wilted simultaneously.
Vernonia marginata	10.2		
Do	9.8		
Do	10.1	10.0	Do.
Artemisia gnaphalodes	9.3		
Do	10.7		
Do	10.0		
Do	10.9		
Do	10.7		
Do	9.9	10.3	Do.
For all determinations, soil No. 30		9.7	
Probable error of mean		± .02	
Probable error of single observation.		± .04	

TABLE XIV.—*Plants grown simultaneously in the same sealed pot with Kubanka wheat, G. I. 1440, but no soil-moisture determinations recorded.*

Plants.	Number of pots.	Notes.
Water cress	8	Wilted simultaneously.
Ranunculus septentrionalis	2	Do.
Ranunculus abortivus	5	Do.
Acorus calamus	2	Wheat wilting; flag dying back.
Peltandra virginica	2	Wilted simultaneously.
Bamboo	2	Do.
Datura stramonium	2	Do.
Adiantum pedatum	3	Do.
Polystichum acrostichoides	4	Do.
Hepatica triloba	2	Do.
Salix sp	2	Do.
Heteranthera reniformis	3	Do.
Allium cepa	3	Wheat wilting; onion dying back.

The results obtained by the method of simultaneous culture are in practical agreement with the determinations already discussed, as will be seen by referring to Tables XIII and XIV.

In nearly every instance the plant under observation wilted simultaneously with the wheat growing in the same pot. The corn showed a little more discoloration than the wheat in some instances, while in the case of the sorghum the leaves did not roll quite so much as the wheat. The emmer showed a tendency to roll more than the wheat. With the remainder of the plants tested the wilting occurred simultaneously with the wheat, as nearly as could be determined.

A single wheat seedling was used in each pot. Since the root distribution of this seedling was not sufficient to permeate the whole mass of soil, we would expect the wilting-coefficient determinations to show in a modified degree the differences exhibited by coarse-

rooted and fine-rooted plants in the preceding determinations. In other words, the wheat plants in the pots occupied also by coarse-rooted plants would tend to give a higher wilting coefficient than those in the pots occupied wholly by fine-rooted plants. This is in accordance with the results obtained, the corn and some of the legumes giving a mean wilting coefficient a little above the average.

The results obtained by observing the relative time of wilting of two different plants growing in the same soil mass are then in accord with the conclusions drawn from a comparison of the wilting coefficients obtained with different plants as indicators, namely, that the differences exhibited by crop plants as regards their ability to reduce the moisture content of the soil before wilting occurs are so small as to be of little practical significance in the selection of crops for semiarid regions. There is no evidence that drought resistance in a plant is due to an additional water supply made available for growth by virtue of a greater ability on the part of that plant to remove moisture from the soil.

METHOD FOR DETERMINING THE WILTING COEFFICIENT FOR PLANTS HAVING NO DEFINITE WILTING POINT.

The wilting coefficient of a given soil can be found for most plants by the method already described. In the case of plants having aerial water-storage tissues or thick, heavy leaves this procedure can not be followed, since they have no well-defined wilting point. The method herein described makes it possible to determine when a plant of this kind is no longer able to obtain water from the soil as rapidly as it is given off to the air by the plant. This condition is analogous to wilting in the case of plants without water-storage tissues.

Let us consider a fleshy plant such as a cactus, the roots of which are well established in a mass of soil contained in an impervious pot, with the surface of the soil sealed to prevent loss of moisture except through the transpiration of the plant. Consider this system supported on knife-edges located on opposite sides of the pot, and suppose the system balanced with suitable counterweights so that it is in stable equilibrium when the plant is in a horizontal position, but with the center of gravity high enough to form a system of some sensibility. This system if set in motion will oscillate about the point of equilibrium. As the plant begins to lose water through transpiration, water will move from the soil to replace the water lost from the plant and the soil end of the system will become lighter and rise in consequence. This process will be repeated as often as the balance of the system is readjusted to the original zero point, until finally the soil is no longer able to supply water to the plant at

a rate sufficient to meet the transpiration requirements. The plant itself will then begin to lose water from its storage tissues and the plant side of the system will consequently become lighter, with the result that the plant will eventually move upward or in an opposite direction to its former motion. The moisture content of the soil at this point is the wilting coefficient.

Between these two extreme conditions there occurs a brief period during which the soil is able to supply some water to the plant, but not in sufficient quantity to offset the amount lost when the transpiration is greatest. During this time the balanced system will

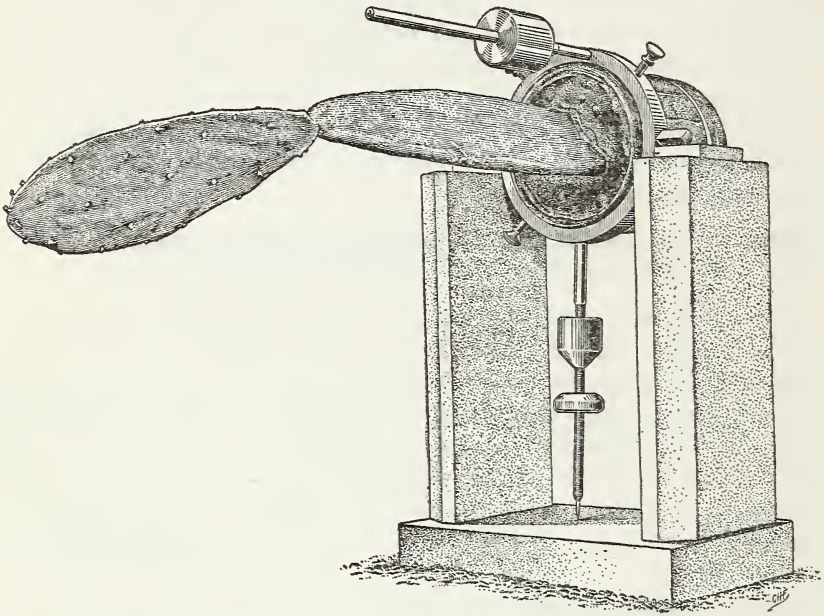

FIG. 2.—Apparatus for determining the wilting coefficient for plants with water-storage tissues. The glass pot containing the cactus is clamped into a brass ring which is supported on knife-edges and provided with suitable weights for adjusting the sensibility and restoring the balance.

appear sluggish and uncertain in its movement, as if no changes in the moisture content were taking place, although weighings made upon the whole system will show that water is being lost.[1]

One form of apparatus which has been used in making these determinations is shown in figure 2. It consists essentially of a brass ring suspended by steel knife-edges which are so inserted that the edges lie in the same straight line. The glass pot is held within this ring and is further supported on two rods extending horizontally

[1] It is possible with a balanced system of this kind to distinguish between absorption and transpiration by determining the loss in weight and the weight which must be added to the soil (or plant) centroid to restore the balance of the system.

from the lower part of the ring. Four thumbscrews working upon rubber packing serve to clamp the glass pot securely into position. A threaded brass rod extends downward from the lowest point of the ring and carries a pointer at its lower end. This rod also carries one or more cylindrical weights, which are screwed up or down on the rod until the desired sensibility is obtained. A second counterpoise carried on a threaded rod parallel to the plant serves to counterbalance the excess weight of the soil over the plant and provides a convenient means of balancing the system. The exact position of this counterpoise can be recorded from day to day, if desired, by a simple scale measurement from the ring to the edge of the counterpoise. A sheet-metal cylinder closed at one end surrounds the glass jar and is held in position by friction on the outside ring. This cylinder is either nickel plated or covered with

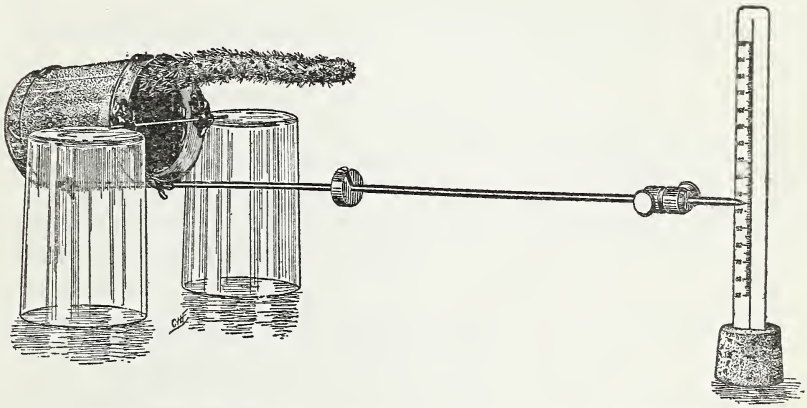

FIG. 3.—Simple apparatus for determining the wilting coefficient for plants with water-storage tissues. The system is suspended from a piece of knitting needle which is cemented to the walls of the pot.

aluminum paint and serves to equalize the temperature of the pot. The surface of the soil is covered with wax composed of a mixture of beeswax and tallow or of paraffin and petrolatum.

When small plants are to be used the apparatus can be very simply set up with the aid of a short length of rod and some suitable cement. An apparatus of this kind is shown in figure 3. The cactus is potted in an ordinary thin-walled drinking glass, the plant being placed at one side of the center and the surface of the soil covered with a layer of wax. As a substitute for knife-edges a piece of a knitting needle is cemented across the top of the glass with De Khotinsky's hard cement,[1] the latter being reenforced with loops of wire cemented to the walls of the pot. A brass rod or heavy wire about 3 millimeters in diameter and 60 or 70 centimeters long is then

[1] This cement softens somewhat in direct sunlight, and the pot should not be left suspended under heat conditions.

bound with fine wire to the outside of the glass and cemented as shown, to serve as a support for the counterpoise. When suspended between suitable supports the system oscillates about its position of equilibrium, which can be adjusted by means of the counterpoise. The end of the counterpoise rod in this case serves as an

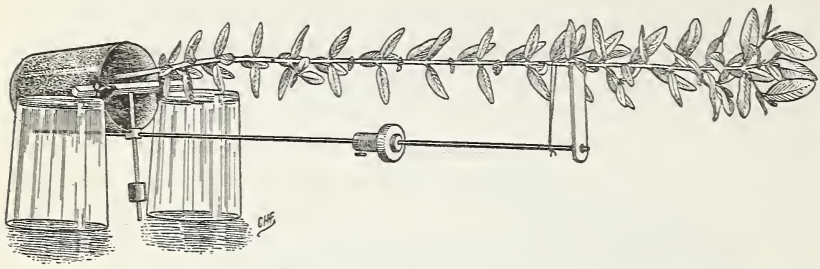

FIG. 4.—Simple apparatus for determining the wilting coefficient for plants which have no sharp wilting point. Knife-edges are employed which render the system much more sensitive than the one shown in figure 3.

index. A vertical rod for changing the sensibility, while convenient, is not necessary in a small system of this kind, as this adjustment can be quite readily made by warming the cement and moving one end of the supporting rod slightly. In the apparatus shown a weight of 1 gram applied at the center of the pot produced a deflection of 20 millimeters at the end of the pointer, so that a change in the moisture content amounting to 0.1 gram was readily observed. This sensibility can be increased by the use of knife-edges as in figure 4.

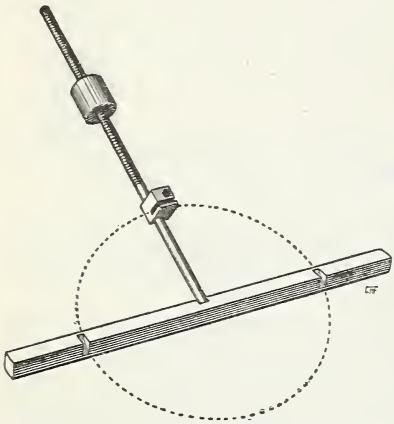

FIG. 5.—Diagram showing the construction of knife-edges. The square rod is milled halfway through at points where it engages the walls of the pot in order to reenforce the cement joint.

Another form of the apparatus is shown in figure 5. Two narrow slots are milled halfway through a piece of ¼-inch square steel, so as to engage the opposite walls of the glass pot, and a rod for adjusting the sensibility of the system is inserted in the center. In attaching the knife-edges to the pot the slots and the edges of the pot are coated with hot cement and forced together.

A convenient counterweight is shown in figure 6. The coarse adjustment is made by sliding the counterweight along the supporting rod, after which it is clamped by the set screw. Exact

adjustment is then effected by means of the threaded nut on the counterweight.

When a fleshy plant with a well-developed root system is used, and the soil contains a suitable amount of water, the system acts essentially as described above. The plant will continually tend to move downward from its initial position of equilibrium, owing to the movement of water from the opposite side of the system to replace the water transpired by the plant. As the soil becomes drier this movement becomes less marked and indeterminate, until finally the direction of motion is reversed, the plant moving upward as its own weight begins to be reduced through the loss of water.

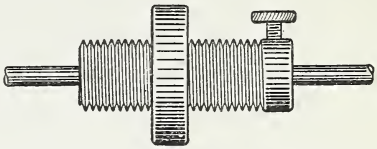

FIG. 6.—A convenient counterpoise weight for use in adjusting the balancing system. A coarse adjustment is effected by moving the counterpoise weight along the rod and clamping with a set screw. A fine adjustment is then made by means of the threaded nut.

This is well illustrated by the observations given in Table XV, showing clearly the three stages characteristic of a balanced system of this kind. The table includes observations made with a balanced cactus plant (*Opuntia ficus indica*) and with a young lemon plant (*Citrus limonum*), the latter serving to show the wilting of the plant which accompanies the change in the direction of motion of the system.

TABLE XV.—*Observations with two balanced systems, one containing a cactus plant and the other a lemon plant.*

Plant and time of observation.	Weight.	Notes.
Cactus plant (*Opuntia ficus indica*):	*Grams.*	
Feb. 8, 5.45 p. m.	648.4	Balanced and adjusted to zero.
Feb. 9, 9.30 a. m.	648.1	Plant down; readjusted to zero.
Feb. 11, 5 p. m.	646.1	Do.
Feb. 13, 5 p. m.	644.8	Do.
Feb. 14, 10 a. m.	644.6	Do.
Feb. 15, 10 a. m.	644.4	Do.
Feb. 16, 9.30 a. m.	644.3	Do.
Feb. 16, 5 p. m.	643.9	Balanced, no change.
Feb. 17, 5 p. m.	643.7	Do.
Feb. 18, 5 p. m.	643.55	Plant up; readjusted to zero.
Feb. 20, 5 p. m.	642.85	Do.
Lemon plant (*Citrus limonum*):		
Dec. 5, 5 p. m.	579.41	Adjusted to zero (*Citrus limonum*).
Dec. 6, 5 p. m.	574.50	Plant down; readjusted to zero.
Dec. 7, 5 p. m.	573.55	Do.
Dec. 8, 5 p. m.	570.85	Do.
Dec. 9, 5 p. m.	568.20	Do.
Dec. 10, 5 p. m.	565.83	Do.
Dec. 12, 5 p. m.	559.85	Do.
Dec. 13, 4 p. m.	557.75	Do.
Dec. 15, 4 p. m.	553.40	Do.
Dec. 17, 4 p. m.	549.54	Do.
Dec. 19, 5 p. m.	545.77	Balanced.
Dec. 20, 5 p. m.	544.16	Plant up; readjusted to zero.
Dec. 21, 5 p. m.	542.56	Plant up; wilting.
Dec. 22, 5 p. m.	541.95	Plant up; wilted.
Dec. 23, 4 p. m.	539.50	Plant up; lower leaves drying.

Reference to the weighings in Table XV will show a continuous loss of water, decreasing somewhat at the time the system reverses its direction of motion. While this loss of water is taking place the soil end of the system at first rises continuously; then the system remains balanced for a short time, and finally the plant end of the system rises. It will be noted that the wilting of the lemon plant followed immediately after the change of direction of motion of the system.

In Table XV is given a series of observations on three balanced systems (Pl. I, fig. 1), two plants being grown in each system, as follows: (1) Cactus and squash, (2) cactus and wheat, and (3) olive and wheat. The cactus is capable of losing a relatively large amount of water without giving visible evidence of loss, while the leaves of the olive will dry and become brittle without wilting or rolling. These two plants form typical examples of cases where it is necessary to resort to a balancing method in order to determine the wilting coefficient.

TABLE XVI.—*Observations with three balanced systems containing three pairs of plants.*

Plants and time of observation.	Weight.	Notes.
Cactus and squash plants:	*Grams.*	
Oct. 1, 9 a. m.	.....	Balanced and adjusted to zero.
Oct. 1, 12.30 p. m.	523.6	Plant down; readjusted to zero.
Oct. 3, 9 a. m.	518.2	Plant up; squash wilted. Rewatered October 4; the squash growing and in good condition.
Oct. 11, 5.30 p. m.	528.9	Balanced and adjusted to zero.
Oct. 12, 5.30 p. m.	525.7	Plants down; readjusted to zero.
Oct. 13, 5 p. m.	523.0	Do.
Oct. 14, 5.30 p. m.	520.9	Do.
Oct. 15, 5.30 p. m.	519.3	Balanced.
Oct. 16, 12 m.	518.0	Plants up; squash wilting; readjusted.
Oct. 17, 12 m.	516.8	Plants up; squash wilted. Squash cut off, resealed, and corrections made for change in weight.
Oct. 17, 5 p. m.	516.3	Plants up; readjusted to zero.
Oct. 18, 9 a. m.	516.0	Do.
Oct. 19, 9 a. m.	515.9	Do.
Cactus and Kubanka wheat plants:		
Feb. 18, 5 p. m.	772.2	System balanced.
Feb. 20, 5 p. m.	768.9	Plants down; readjusted to zero.
Feb. 21, 4 p. m.	763.5	Do.
Feb. 22, 4 p. m.	762.7	Do.
Feb. 23, 4 p. m.	758.8	Do.
Feb. 24, 5.30 p. m.	754.3	Do.
Feb. 25, 4 p. m.	750.0	Do.
Feb. 27, 4 p. m.	744.95	Plants balanced.
Feb. 28, 4.30 p. m.	743.1	Plants up; wheat rolled and wilted.
Mar. 1, 9.30 a. m.	742.5	Do.
Mar. 2, 9.30 a. m.	741.1	Do.
Olive and Kubanka wheat plants:		
Feb. 28, 5 p. m.	520.2	Balanced and adjusted to zero.
Mar. 1, 9.30 a. m.	517.62	Plants down; readjusted to zero.
Mar. 1, 4.30 p. m.	511.15	Do.
Mar. 2, 9.30 a. m.	507.9	Do.
Mar. 2, 5.15 p. m.	501.6	Do.
Mar. 3, 10 a. m.	499.5	Do.
Mar. 3, 5.30 p. m.	494.6	Do.
Mar. 4, 5 p. m.	491.25	Do.
Mar. 5, 12 m.	490.4	Balanced.
Mar. 6, 10 a. m.	488.0	Balanced; wheat wilting.
Mar. 6, 4.30 p. m.	487.0	Do.
Mar. 7, 9.30 a. m.	486.5	Plant up; wheat wilting.
Mar. 8, 10 a. m.	485.8	Do.

Referring to the record of observations with the cactus and the squash, it will be seen that the reversal of the direction of the motion

of the system accompanied the wilting of the indicator plant. This is not due to the loss of water from the indicator plants alone, for the record shows that a steady loss of water took place from the soil from October 11 to October 14. On October 15, however, the system was found balanced. On October 16 the plant end of the system was up, indicating the loss of water from the plant tissues, and the squash was found wilting. The squash was cut off below the wax and the pot resealed, weighed, and again balanced on October 17. After five hours the plant end of the system was again up, showing the simultaneous loss of water from the growing tissues of the cactus. In other words, the cactus loses water from its storage tissues at the time the squash plants wilt, which means that the cactus is initially no more effective than the squash in reducing the moisture content of the soil. The two plants therefore have the same wilting coefficient.

Precisely similar results were obtained for cactus and Kubanka wheat, and with the olive and wheat. The results afford no ground for believing that either the cactus or the olive can reduce the moisture content of the soil below the point at which other plants wilt without simultaneously reducing the water content of its aerial tissues.

CAUSES OF VARIATION IN WILTING-COEFFICIENT DETERMINATIONS.

In making determinations of the wilting coefficent, variations of greater or less magnitude occur. These variations are found even though a single strain is used as an indicator, and when individual variation is minimized by growing five plants or more of the same strain in each pot. The causes for such variation may be treated under two headings: (1) Causes for determinations having a value less than normal and (2) causes for determinations having a value greater than normal.

CAUSES FOR DETERMINATIONS HAVING A VALUE LESS THAN NORMAL.

This condition is generally due to direct evaporation from the soil. It is evident that the moisture evaporated directly into the air may reduce the moisture content of the soil on the surface or outer portions of the soil mass far below that to which it could be reduced by the plant at the time of wilting. In our experiments this source of error has been avoided by using impervious pots and a wax seal. In the experiments of earlier investigators, however, this must have been a constant source of error. In field determinations this constitutes an almost insurmountable source of error or uncertainty, since it is difficult to determine to what extent direct loss of water from the soil has continued in the upper layers while the plant was drawing upon some deeper source of moisture.

Another cause of low determinations is found in allowing plants to stand too long after they have reached a wilted condition. As has been shown, plants continue to extract moisture from the soil even after they have reached a wilted state, and this loss continues even after the death of the plant. It is evident, therefore, that if a plant is allowed to stand for any considerable period after it has once reached a permanently wilted condition the determination of soil moisture will be below the true wilting coefficient. This is a source of considerable error, especially with plants which do not wilt readily. An example of such plants is the olive, which, if one were to rely entirely upon the outward signs, would reduce the moisture in the soil far below the wilting coefficient. It is very easy to demonstrate by means of the balancing method that in such cases the plant has long since passed the point corresponding to the wilting coefficient, i. e., the point of permanent decrease of the water content of the leaf cells. The determination at the time the leaves curl or drop is not a true measure of the wilting coefficient, but of the moisture content at some point between the wilting coefficient and the hygroscopic coefficient of the soil. It is therefore essential in making these determinations that considerable care be exercised in avoiding the excessive wilting of the plants used.

A third source of error results from the distillation of water from one portion of the soil mass to another. The pot standing in the open becomes warm during the day. During the early evening, when the air cools below the temperature of the soil, rapid distillation of water takes place and the water is driven out of the warmer soil and condenses on the sides of the pot, which are cooler than the soil. This distillation can be observed even in a comparatively dry soil, and plants which are allowed to stand in pots exposed to this temperature fluctuation develop an extensive surface root system. This distillation taking place in the ordinary greenhouse once or twice a day is sufficient to maintain the plants in fairly good condition long after the soil has been reduced below the wilting coefficient. In early experiments this distillation was found to be a serious source of error. In the later experiments this error has been avoided by means of the constant-temperature bath.

With the precautions which have been employed the errors due to obtaining too low a wilting-coefficient determination are comparatively slight, and it has been possible to eliminate practically all of the errors under this head. It seems likely, however, that the early investigators who concluded that there were comparatively great differences in the ability of different plants to remove moisture from the soil were largely misled as a result of the errors which have been noted above

CAUSES FOR DETERMINATIONS HAVING A VALUE GREATER THAN NORMAL.

The errors under this heading are far more serious than those under the heading just discussed and are more difficult to eliminate entirely. One source of error is in assuming that a temporarily wilted condition is the permanently wilted condition. A temporarily wilted condition generally results from a rapid increase in the saturation deficit combined with an increase in temperature and light intensity, which result in greatly increasing the transpiration of the plant. Many plants, such as tobacco and corn, normally show temporary wilting during the hot part of the day, and the same is observed in many different plants if the conditions are sufficiently severe. This source of error may be avoided by placing the wilted plants under a bell jar in a comparatively saturated atmosphere. If they fail to recover, the wilted condition may be regarded as permanent. If, however, they soon resume their normal condition the wilting has been merely temporary. Such temporary wilting has not been encountered very generally in our experiments. Plants grown under ordinary greenhouse conditions seldom show temporary wilting, and by a little care in maintaining equable conditions the difficulty can be entirely avoided. As we have shown above, the degree of humidity or of light intensity does not appear to affect the wilting coefficient so long as conditions are uniform, but a sudden increase in temperature, light intensity, and saturation deficit often brings about a sudden temporary wilting which may lead to error.

Occasionally a pathological condition is encountered, the plant roots or even the top being affected by some parasite, causing the plant to wilt as if the water supply were inadequate. Such abnormal conditions can be detected easily by an examination of the plants at the time the sample is taken. If it is evident that the plant is in a diseased condition moisture samples should not be taken.

The third and greatest cause of uncertainty in the determination of the wilting coefficient is found in imperfect root distribution. The results of the experiments herein recorded indicate that to a very great extent the variations in the wilting coefficient for different plants are dependent upon the degree to which the roots of the plants penetrate every portion of the soil mass. An ideal determination of the wilting coefficient would be one in which every portion of the soil was brought into contact with the plant roots. This ideal condition is never reached. Some plants, particularly the grasses, when planted in a pot approach this condition more nearly than any others tried, and with these forms a lower wilting-coefficient determination was obtained. Other plants, especially those having large, coarse roots and which develop few rootlets, give a correspondingly high wilting coefficient.

The highest determination recorded probably accompanies a root distribution such that the water must move through relatively long distances in the soil by capillary action. The lowest determination will be reached only when the root distribution is perfect. It is obvious that in all measurements of the wilting coefficient variations may be found anywhere between these two conditions as limits.

The tables show that plants having finely divided roots give uniformly a lower determination than those with larger roots, irrespective of whether they grow normally in arid or humid regions (Table XII). An effort has been made to secure a condition of uniformity in the root distribution by using a small pot and by keeping the roots well within the soil mass as a result of the equalized temperature; but with some plants, notably the dasheen (*Colocasia* sp.), as well as some of the larger rooted western plants which have given a rather imperfect root distribution, a wilting-coefficient determination somewhat higher than normal has been obtained.

As already stated, it is believed that the differences observed in the wilting coefficient for different plants are largely due, not to the ability of one variety to exert a greater pull on the soil moisture than another variety, but to the more perfect root distribution of one variety as compared with another.

INDIRECT METHODS OF DETERMINING THE WILTING COEFFICIENT.[1]

In field studies of soil moisture, determinations of the total water content can easily be made. The errors which enter into the determination of the wilting coefficient under field conditions are relatively great, owing to the direct evaporation from the soil, local variation in soil texture, and lack of uniformity in the root distribution, combined with the difficulty of determining the exact wilting point when the roots occupy a large soil mass. Furthermore, it is only during periods of extreme drought that conditions are favorable for wilting-coefficient determinations in the field. In view of these difficulties it becomes important to ascertain whether the soil-moisture content at the wilting point can be determined by an indirect method, based upon the relationship of the wilting coefficient to the moisture retentiveness of the soil as measured by physical methods.

RELATION OF THE WILTING COEFFICIENT TO THE MOISTURE EQUIVALENT.

The moisture equivalent of the soil is the percentage of water which it can retain in opposition to a centrifugal force 1,000 times that of gravity.[2] In making the determinations the soils are placed

[1] Kubanka wheat, G. I. 1440, was used as the indicator plant.

[2] Briggs, L. J., and McLane, J. W. The Moisture Equivalents of Soils. Bulletin 45, Bureau of Soils, U. S. Dept. of Agriculture, 1907.

in perforated cups and moistened with an amount of water in excess of the quantity they can hold in opposition to the centrifugal force. After standing 24 hours the cups are placed in a centrifugal machine which is operated at a constant speed so chosen as to exert a force 1,000 times that of gravity upon the soil moisture. Each soil then rapidly loses water until the capillary forces are increased sufficiently to establish equilibrium with the centrifugal force employed. The moisture content of each soil is now not only in equilibrium with a force 1,000 times that of gravity, but is also in capillary equilibrium with every other soil which has been similarly treated, so that if the soils are placed in capillary contact in any combination whatever, no movement of water from one soil to another will occur. The moisture content of each soil under these conditions is the moisture equivalent of that soil. This method provides a means of determining and comparing the retentiveness of different soils for moisture when acted upon by a definite force, which is measured in absolute terms and is reproducible within narrow limits.

Table XVII gives a comparison of the wilting coefficient and the moisture equivalent for a series of soils ranging in texture from a coarse sand to a clay. The names applied to the soils have been determined from the mechanical analyses in accordance with the soil-classification table used by the Bureau of Soils.[1] The soils are arranged in the order of increasing moisture equivalents. For the moisture-equivalent determinations the writers are indebted to Mr. J. W. McLane. All moisture determinations are expressed as percentages of the dry weight of the soil used.

TABLE XVII.—*Relation of the wilting coefficient to the moisture equivalent of soils ranging from sand to clay.*

Soil.	Types of soil.	Moisture equivalent.	Coefficient.		Ratio of moisture equivalent to coefficient.
			Number of determinations.	Average.	
7	Coarse sand	1.6	11	0.9	1.78
2	Fine sand	4.7	16	2.6	1.81
8	.....do	5.5	3	3.3	1.67
9	.....do	6.7	2	3.6	1.86
3	Sandy loam	9.7	9	4.8	2.02
10	.....do	11.9	3	6.3	1.89
4	Fine sandy loam	18.1	13	9.7	1.87
12	Loam	18.9	3	10.3	1.83
A	Sandy loam	19.6	1	9.9	1.98
B	Fine sandy loam	19.9	1	10.8	1.84
C	.....do	22.1	1	11.6	1.90
5	Loam	25.0	12	13.9	1.80
D	.....do	27.0	1	15.2	1.78
13	Clay loam	27.4	2	14.6	1.88
14	.....do	29.3	4	16.2	1.81
E	.....do	30.0	1	16.5	1.82
6	.....do	30.2	16	16.3	1.85
	Mean				1.84
	Probable error of mean				± .013

[1] Soil Survey Field Book, Bureau of Soils, U. S. Dept. of Agriculture, 1906, pp. 17–18.

The moisture-equivalent determinations given in the table represent in each case the mean of two determinations. The number of wilting-coefficient determinations made upon each soil is shown in column 4, and the mean of these determinations is given in column 5. The last column gives the ratio of the moisture equivalent to the wilting coefficient for each soil.

The table shows that the soils used in the comparison cover a wide range in moisture retentiveness, the moisture equivalent increasing from 1.6 per cent in sand to over 30 per cent in the clay loam, while the wilting coefficient ranges from 0.9 per cent in sand to 16.5 per cent in the clay loam. The mean ratio of the moisture equivalent to the wilting coefficient for all the soils examined is 1.84. The probable error of this mean is ± 0.013; that is to say, considering the series to be representative of soils as a whole, the chances are even that if a similar series of determinations were made the mean of the ratios would fall between 1.827 and 1.853.

It will be noted that the greatest departures in the ratios are found among the sandier soils. This is due to the fact that a slight experimental error in determining either the moisture equivalent or the wilting coefficient affects the ratio markedly, owing to the small percentages of moisture retained by these soils.

The significant feature of the results here presented is the fact that through the wide range of moisture retentiveness exhibited by the soils employed, the ratio of the moisture equivalent to the wilting coefficient appears to be constant within the limits of experimental error. In other words, two determinations of the moisture retentiveness of these soils, one physical and the other physiological, show a linear relationship which is independent of the texture of the soil. This relationship is expressed by the following formula:

$$\frac{\text{Moisture equivalent}}{1.84 \pm 0.013} = \text{wilting coefficient.}$$

In order to compare the moisture available for growth in one soil with that in another, we must know or be able to estimate accurately the wilting coefficient of each soil. The minimum limit of moisture available for growth is the datum line from which all comparisons should be made. This datum can be established directly by wilting-coefficient measurements, or it may be calculated by means of the ratio just established. The latter method is by far the simpler and more expedient for field work. The soil sample taken in the field for soil-moisture determination, although ample for duplicate measurements of the moisture equivalent, is usually not large enough for a single wilting-coefficient determination. Moreover, the period of time required for wilting-coefficient determinations, combined with

the uncertainty which accompanies all physiological work when duplication is impossible, makes this determination less expedient, and the results in such cases less reliable than those derived from the moisture equivalent by the use of the ratio here established.

ADDITIONAL DATA ON THE RELATION OF THE WILTING COEFFICIENT TO THE MOISTURE EQUIVALENT.

At the time of making the experiments the results of which are given in Table XVII, a clay loam having a moisture equivalent of about 30 per cent was the heaviest type of soil that was available. After developing the relationship between the moisture equivalent and the wilting coefficient, it was desired to determine whether this relationship held also for very heavy soils. Accordingly, a similar series of determinations was made with clay soils from near Bellefourche, S. Dak., which are derived from the Pierre shale and include the heaviest soils which we have seen. The results of these determinations are given in Table XVIII. The moisture equivalents of these samples range from 32 to 57 per cent, while the wilting coefficients range from about 17 to nearly 31 per cent. In other words, plants wilt in the heaviest types when the soil-moisture content is over 30 per cent, showing the remarkable moisture retentiveness of these soils as compared with dune sand, in which the wilting coefficient is less than 1 per cent.

TABLE XVIII.—*Relation of the wilting coefficient to the moisture equivalent of heavy clay soils from Bellefourche, S. Dak.*

Soil.	Moisture equivalent.	Coefficient.		Ratio of moisture equivalent to coefficient.
		Number of observations.	Mean.	
P	31.9	3	16.8	1.89
Q	40.2	2	22.2	1.82
R	43.5	3	23.3	1.86
S	44.9	2	24.2	1.85
T	45.7	3	25.9	1.78
U	48.8	3	25.7	1.90
V	52.4	3	27.4	1.91
W	56.2	3	30.4	1.84
X	57.0	3	30.9	1.84
Mean				1.85
Probable error of mean				± .02

The mean ratio of the moisture equivalent to the wilting coefficient for these heavy types of soil was 1.85, with a probable error of ±0.02. The mean ratio agrees, then, within its probable error, with the result given in Table XVII. In other words, the relationship established from the determinations given in that table holds also for the heaviest soil types.

The wilting-coefficient determinations given in Tables XI and XIII also provide an opportunity for testing this relationship. For this purpose use is made of the mean wilting coefficient as determined from all the plants tested in each soil, which is given at the end of the measurement for each soil in Table XI (except No. 30, which is given in Table XIII). For convenient reference, these mean wilting coefficients have been collected in Table XIX, together with the moisture equivalent for each sample, and the ratio determined as before. The mean value of all the ratios is 1.85, with a probable error of ±0.02. This ratio also agrees, within the probable error, with the mean ratio obtained from the results in Table XVII. In the results given in Tables XVII and XVIII, Kubanka wheat alone was used as an indicator plant. From the results given in Table XIX, it is seen that the same ratio between the moisture equivalent and the wilting coefficient is obtained when many different plants are used as indicators. This result accords with the idea already advanced that the difference resulting from using different varieties or different crops as indicator plants is slight. The agreement obtained through a wide range of soils and with different plants as indicators leads to the belief that the relationship given is quite general in its application and sufficiently accurate to meet field requirements in determining the wilting coefficient.

TABLE XIX.—*Ratio of the moisture equivalent of the soils covered by Tables XI and XIII to the mean wilting-coefficient determinations of those soils.*

Soil.	Types of soil.	Moisture equivalent.	Wilting coefficient.		Ratio of moisture equivalent. to coefficient.
			Number of determinations.	Mean.	
1	Coarse sand	1.55	11	0.86	1.81
7	.....do	1.55	59	1.03	1.51
87	Sand	2.48	8	1.23	2.01
2	Fine sand	4.66	18	2.6	1.79
8	.....do	5.5	42	3.03	1.82
9	.....do	6.74	44	3.76	1.79
80	Sandy loam	.....	15	4.2	.....
3	.....do	9.7	14	4.8	2.02
10	.....do	12.0	45	6.3	1.91
82	.....do	14.5	11	7.8	1.86
4	Fine sandy loam	18.1	36	9.3	1.95
30	.....do	18.5	418	9.7	1.91
26	Sandy loam	18.6	64	8.84	2.10
12	Loam	18.9	45	10.4	1.82
86	Clay loam	23.3	9	13.4	1.74
78	Loam	23.8	34	12.7	1.87
5	.....do	25.0	13	13.9	1.80
13	Clay loam	27.4	55	14.8	1.85
14	.....do	29.3	33	17.1	1.71
6	.....do	30.2	16	16.3	1.85
	Mean	.....	.....	.....	1.85
	Probable error of mean	.....	.....	.....	± .02

The results given in Tables XVII and XVIII are combined graphically in figure 7, in which the wilting coefficients are given

as ordinates and the corresponding moisture equivalents as abscissas. The graph is a straight line passing through the origin, and the slope is the reciprocal of 1.84.

APPLICATION OF INDIRECT WILTING-COEFFICIENT DETERMINATIONS TO THE INTERPRETATION OF FIELD MOISTURE DETERMINATIONS.

The value of the wilting coefficient as calculated from the moisture equivalents is shown in connection with the following field determinations of soil moisture made at Akron, Colo., in 1910.[1]

The data presented graphically in figure 8 represent daily moisture determinations in 1-foot sections to a depth of 6 feet in a soil in which

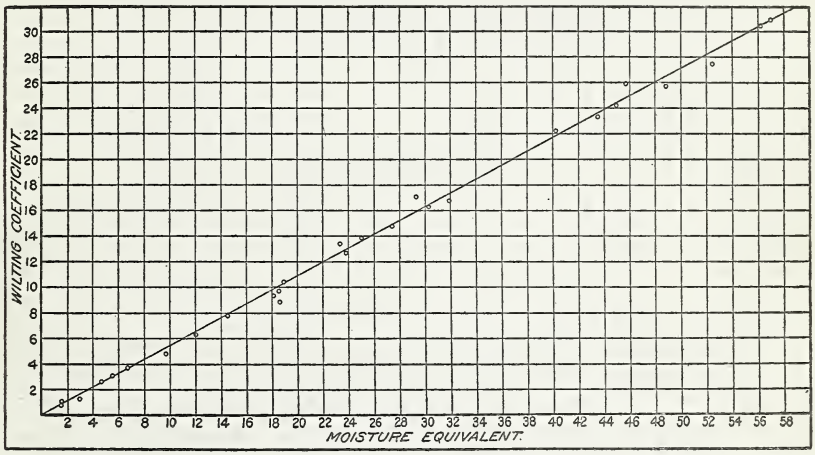

FIG. 7.—Chart showing the linear relationship between the wilting coefficient and the moisture equivalent for 28 types of soil ranging in texture from coarse sands to the heaviest clays.

Kubanka wheat, G. I. 1440, was growing. The determinations are of special interest, owing to the fact that the total rainfall during the seven weeks represented in the chart was only 1.09 inches and was distributed in five showers, as follows: June 25, 0.31 inch; June 30, 0.05 inch; July 2, 0.30 inch; July 5, 0.38 inch; July 22, 0.05 inch. Total, 1.09 inches. None of these rains penetrated beneath the layer of air-dried surface soil. The rainfall during the whole period can, then, be eliminated so far as its influence upon the available moisture is concerned.

The following field notes show the stage of development and condition of the crops during this period:

June 9. Sampling started; average height of leaves at this time, when extended 8 inches; average dry weight per stem, 0.6 gram.

June 21. Very dry; plants not wilted but color seems lighter; awns just coming through; lower leaves and small plants drying up rapidly.

June 24. Heads just out of the boot.

[1] See also Shantz, H. L. Natural Vegetation as an Indicator of the Capabilities of Land for Crop Production in the Great Plains Area. Bulletin 201, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1911, pp. 30-33.

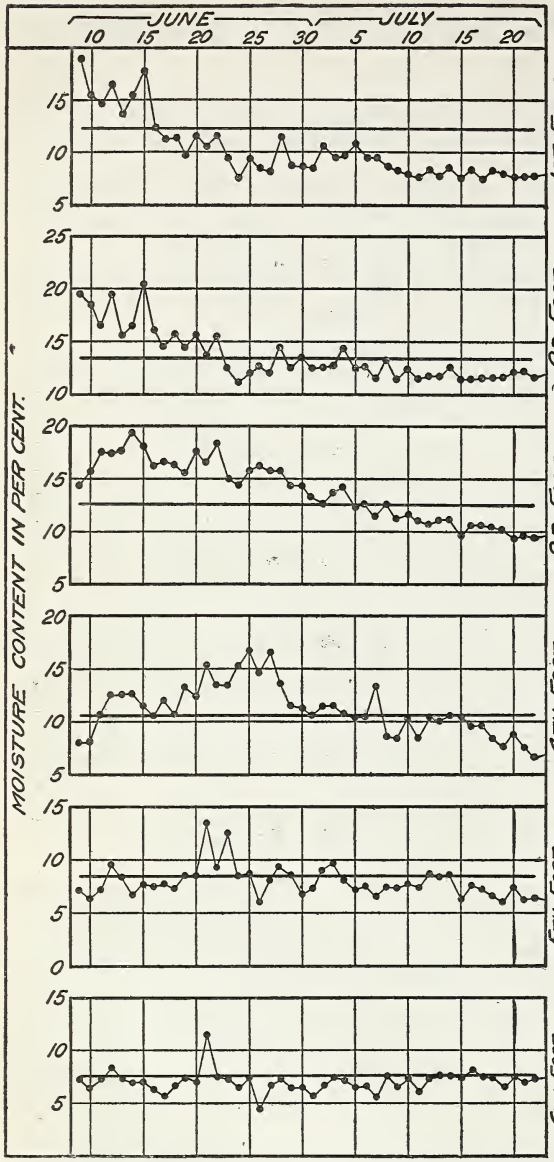

FIG. 8.—Chart showing the daily moisture determinations in 1-foot sections to a depth of 6 feet in a soil on which Kubanka wheat was growing. The heavy horizontal straight lines on the chart represent the wilting coefficient as calculated from the moisture equivalent independently of the moisture determinations or of field observations. The wheat wilted on July 1 and was cut July 22. The graphs show that the moisture curves are either coincident with or below the wilting coefficient on July 1, indicating that there was no longer moisture available for growth. The continuous loss of water from the soil after wilting takes place is also shown.

June 26. Wheat well headed; just about to wilt.

June 27. In good condition.

NOTE.—Weather cool and cloudy during June 26, 27, and 28.

July 1. Beginning to wilt.

July 4. Almost dry.

July 7. Almost dead.

July 8. About two-thirds of the stem is dry.

July 9. Leaves nearly all dead.

July 10. No evidence that the plants are getting water.

July 11. Very dry.

July 19. Extremely dry.

July 22. Dead ripe; harvested.

The heavy horizontal straight line shown in connection with the determinations for each foot-section represents the calculated value of the wilting coefficient. This value was calculated by means of the relationship already established from moisture-equivalent determinations made upon a composite of all the samples taken in that section. It is thus entirely independent of any direct

observations of the wilting of the crop. A study of the moisture curve shows that the moisture in the first foot was reduced to the wilting coefficient on June 16; and in the second foot on June 23. At this time the field notes show that the plants were beginning to suffer from lack of moisture. The larger plants were apparently drawing their principal moisture supply from the third foot. The smaller plants with more restricted root systems were confined to soil masses whose water content had been reduced below the wilting coefficient.

The plants continued to show evidence of lack of sufficient moisture until June 27, although wilting did not actually occur. On this date a decided improvement in their condition was noted, due to cool, cloudy weather for three successive days and to the fact that the root systems were beginning to extract moisture from the fourth foot. Hot dry weather followed, and by July 1 the crop was beginning to wilt. It is significant that at this time all of the moisture curves are either practically coincident with or below the line representing the calculated wilting coefficient. In other words, the wilting of the plants occurred simultaneously with the exhaustion of the soil moisture available for growth, as calculated in a wholly independent way from the moisture-equivalent determinations.

After July 1 the crop never recovered and from this time gradually dried and ripened. However, the curves show that the loss of water from the 4 feet of soil through which the roots had penetrated continued even after the plants had died.

The data presented show clearly that the wilting coefficient determined indirectly in the laboratory is applicable to field conditions and that by the use of the ratio already established it is possible to estimate with sufficient accuracy for field purposes the moisture content at which plants growing under field conditions will become permanently wilted. A study of the moisture curves also shows that it is practically impossible to measure the wilting coefficient by means of field samples. There is no way of determining in an unconfined soil mass the zone from which the plant draws its moisture supply at the time of wilting. The upper soil mass is usually reduced below the wilting coefficient long before wilting actually takes place; while, if the samples are taken from the extreme limit of the root system, soil masses which have not been penetrated may contain moisture in excess of the wilting coefficient. Moreover, comparisons of field determinations of the wilting coefficient of two plants have no significance whatever unless the relative moisture retentiveness of the two soil samples has been independently determined. This is well illustrated in the chart, the wilting coefficient ranging from 13.5 to 7.5 per cent in the different foot-sections. In other words,

the third foot-section with 13.5 per cent of water is reduced to its wilting coefficient, while if the sixth foot-section had 13.5 per cent of water it would contain 6 per cent of water available for growth.

OTHER INDIRECT MEASUREMENTS OF THE WILTING COEFFICIENT.

The relationship established between the wilting coefficient and the moisture equivalent led to the belief that a similar relationship might be found for some of the other physical measurements of soil-moisture retentivity. Accordingly similar comparisons were made of the wilting coefficient with the hygroscopic coefficient, the moisture-holding capacity, and the soil texture, as expressed by mechanical analysis. The last-mentioned determination does not measure moisture retentivity, but it does measure certain properties of the soil which determine the moisture retentivity to a large extent. The results of those comparisons will now be considered.

RELATION OF THE WILTING COEFFICIENT TO THE HYGROSCOPIC COEFFICIENT.

When a dry soil is placed in a saturated atmosphere it will absorb water vapor until a condition of approximate equilibrium is attained. The moisture content of a soil under such conditions is known as the hygroscopic coefficient of that soil.

The determination of the hygroscopic coefficient, unless carried out with special precautions, is not very exact. It is influenced by variation in temperature and by any departure from a condition of complete saturation of the surrounding air.[1] The time element is also an important factor, since the soil absorbs water very slowly, particularly near the point of equilibrium. In fact, equilibrium, theoretically, would not be obtained until the interstitial spaces of the soil were practically filled with water. The method thus has certain inherent disadvantages which are not encountered in moisture-equivalent determinations. The hygroscopic-moisture determinations given in this paper were carried out in a double-walled ice chest kept in a subterranean room, where the temperature was approximately 20° C.[2] The bottom of the chest was covered with water and the zinc walls were lined with blotting paper, which was kept saturated.

A comparison of the hygroscopic coefficient and the wilting coefficient for a number of soils is given in Table XX. The soils used are the same as those employed in the preceding experiments, being arranged in the order of increasing moisture equivalents.

[1] Hilgard, E. W. Soils, New York, 1906, p. 196.

[2] Determinations by Mr. J. W. McLane.

TABLE XX.—*Relation of the wilting coefficient to the hygroscopic coefficient of soils ranging from sand to clay.*

Soil.	Types of soil.	Hygroscopic coefficient.	Wilting coefficient.		Ratio of hygroscopic coefficient to wilting coefficient.
			Number of determinations.	Average.	
7	Coarse sand	0.5	11	0.9	0.556
2	Fine sand	1.5	16	2.6	.577
8	do	2.3	3	3.3	.698
9	do	2.3	2	3.6	.639
3	Sandy loam	3.5	9	4.8	.729
10	do	4.4	3	6.3	.699
4	Fine sandy loam	6.5	13	9.7	.670
12	Loam	7.8	3	10.3	.757
A	Sandy loam	6.3	1	9.9	.636
B	Fine sandy loam	6.6	1	10.8	.611
C	do	7.5	1	11.6	.646
5	Loam	9.8	12	13.9	.705
D	do	9.6	1	15.2	.631
13	Clay loam	11.8	2	14.6	.808
14	do	13.2	4	16.2	.815
E	do	11.2	1	16.5	.679
6	do	11.4	16	16.3	.700
	Mean				.680
	Probable error of mean				± .012

The hygroscopic determinations given in the table are the mean of duplicate measurements. The determinations range from 0.5 per cent in sand to 13.2 per cent in clay loam. The corresponding wilting coefficients have been discussed in connection with Table XVII.

The ratio of the hygroscopic coefficient to the wilting coefficient is given for each soil in the last column of Table XX. The mean of this ratio is 0.68, with a probable error of ± 0.012. This ratio presents a second method of determining the wilting coefficient when the hygroscopic coefficient is known, as follows:

$$\frac{\text{Hygroscopic coefficient}}{0.68 \pm 0.012} = \text{wilting coefficient.}$$

Heinrich[1] determined the nonavailable moisture in six types of soil, using corn and oats for indicator plants. He also measured the hygroscopic coefficient of each soil used in his experiments. Computed from his measurements, the mean ratio of the hygroscopic coefficient to the wilting coefficient, together with the probable error of the mean, gives the value 0.696 ± 0.03, as compared with the ratio 0.68 ± 0.01 obtained from our experiments. While Heinrich's determination show more variation than our own, the ratio obtained from his results agrees within the limits of his probable error with the

[1] Heinrich, R. Zweiter Bericht über die Verhältnisse und Wirksamkeit der landwirtschaftlichen Versuchs-Stationen zu Rostock, 1894, pp. 28-32.

ratio obtained in our experiments. A single determination by Alway [1] in which barley plants were used gave a ratio of 0.65.

In the absence of a more definite relationship between the wilting coefficient and the hygroscopic coefficient, Alway [2] has advocated deducting the hygroscopic coefficient from the field soil-moisture determinations as a basis for comparing the available moisture in soils. Our measurements, however, show that the wilting coefficient is about 1.47 times the hygroscopic coefficient, so that very misleading results may be obtained from this approximation, particularly when the moisture supply is limited. For example, consider two soils containing, respectively, 14.7 per cent and 20 per cent of water and each having a hygroscopic coefficient of 10 per cent. Under these conditions all the water in the first soil is practically nonavailable for growth, while the second contains over 5 per cent of available moisture. Simply deducting the hygroscopic coefficient would lead to the erroneous conclusion that both soils contained considerable moisture available for growth.

It is important in this connection to distinguish clearly between the hygroscopic coefficient, as used above, and the hygroscopic water content, which is simply the water content of "air-dry" soil. The latter term has recently been used by Duggar [3] who, in discussing Heinrich's results as given by Cameron and Gallagher,[4] says:

> It will be noticed that so soon as the amount of water in ordinary soil becomes about three times the hygroscopic water content, it begins to assume physiological importance.

The water content of air-dried soil may vary according to atmospheric conditions from practically zero in the case of some sun-dried desert soils to the hygroscopic coefficient when exposed in a saturated atmosphere. There is, consequently, nothing definite or reproducible about such determinations, unless the conditions under which the measurements were made are also known, and any ratio derived from such measurements is likely to give misleading results when applied to other determinations.

RELATION OF THE WILTING COEFFICIENT TO THE SATURATION COEFFICIENT AND TO THE MOISTURE-HOLDING CAPACITY OF SOILS.

The saturation water content or the saturation coefficient is the percentage of water held in the soil when all interstitial space is filled

[1] Alway, F. J. Some Soil Studies in Dry-Land Regions. Bulletin 130 (Dry-Land Agriculture), Bureau of Plant Industry, U. S. Dept. of Agriculture, 1908, pp. 17–42.

[2] Alway, F. J. Studies of Soil Moisture in the Great Plains Region. Journal of Agricultural Science, vol. 2, 1908, p. 334.

[3] Duggar, B. M. Plant Physiology, 1911, pp. 56–57.

[4] Cameron, F. K., and Gallagher, F. E. Bulletin 50, Bureau of Soils, U. S. Dept. of Agriculture, pp. 57–58. An error occurs in Cameron and Gallagher's paper in connection with Heinrich's results. They give his determinations on air-dried soils, but state that these determinations were made after exposing the soils to a saturated atmosphere for a week.

with water. The moisture-holding capacity is the percentage of water a soil can retain in opposition to the force of gravity when free drainage is provided. This is dependent on the height of the soil column employed, diminishing as the height of the column is increased.[1] When the soil column is made very short—for example, 1 centimeter in height—the two determinations are practically identical. Both are greatly influenced by the packing and the granulation of the soil, so that determinations are subject to wide variation in the hands of different observers.

In Table XXI the wilting coefficients of a series of soils [2] are compared with their moisture-holding capacity. Following Hilgard,[3] determinations of moisture-holding capacity were made with a soil column 1 centimeter in height, with free drainage.

TABLE XXI.—*Relation of the wilting coefficient to the moisture-holding capacity of different soils.*

Soil.	Types of soil.	Moisture-holding capacity.	Wilting coefficient.	Ratio of moisture-holding capacity −21 to wilting coefficient.
7	Coarse sand	23.2	0.9	2.44
2	Fine sand	29.9	2.6	3.40
8	do	28.5	3.3	2.27
9	do	31.4	3.6	2.84
F	Sandy loam	44.9	8.3	2.88
G	do	50.1	9.5	3.06
H	Loam	55.9	11.0	3.17
I	do	58.6	11.6	3.24
J	do	59.8	11.7	3.30
86	Clay loam	54.2	13.8	2.40
K	do	58.2	14.7	2.52
L	do	63.2	14.9	2.83
M	do	71.3	15.0	3.35
N	do	67.2	15.7	2.94
O	do	69.5	16.7	2.90
	Mean			2.90
	Probable error of mean ratio			± .06

The moisture-holding capacity of the soils used in the comparison ranged from about 23 to about 71 per cent. In this case the ratio between the moisture-holding capacity and the wilting coefficient is not constant. However, an approximately constant relationship is obtained if the moisture-holding capacity (expressed as a percentage) is first reduced by 21. The ratio of the moisture-holding capacity less 21 to the wilting coefficient is shown in the last column of the table. The mean ratio for the 15 soils examined is 2.90 ± 0.06. The

[1] Loughridge, R. H. Investigations in Soil Physics. Report, California Agricultural Experiment Station, 1892–1894, p. 99.

Briggs, L. J. The Mechanics of Soil Moisture. Bulletin 10, Division of Soils, U. S. Dept. of Agriculture, 1897.

[2] In this work it was not possible to obtain samples of all the soils used in the preceding experiments.

[3] Hilgard, E. W. Soils, New York, 1906, p. 209.

relationship between the wilting coefficient and the moisture-holding capacity is then expressed by the formula:

$$\frac{\text{Moisture-holding capacity} - 21}{2.9 \pm 0.06} = \text{wilting coefficient.}$$

RELATION OF THE WILTING COEFFICIENT TO SOIL TEXTURE AS EXPRESSED BY MECHANICAL ANALYSIS.

Soil texture has been used for the quantitative description of soils more extensively than any other physical property, and unfortunately it has been one of the most difficult to interpret from the standpoint of moisture retentiveness. Texture is quantitatively expressed by means of the mechanical analysis, which shows the composition of the soil when the particles are separated into groups according to size. The accuracy with which the texture of the soil can be expressed by this means is dependent on the number of groups into which the particles are separated. But the difficulty of effecting a complete separation of the finer particles into the desired groups places a practical limit upon the number of groups, which is usually limited to seven.[1]

The use of mechanical analysis as a basis for determining the moisture retentiveness of a soil is further complicated by the fact that soils having a high clay content will show great differences in the amount of colloidal material, which greatly affects the moisture retentiveness. Furthermore, the particles constituting a given group may lie much nearer one limit of the group than the other, so that a given group does not always have the same properties. Consequently the particles constituting a given group in the mechanical analysis do not always have the same moisture retentiveness per unit mass. It is also possible that the specific retentivity of a group when measured alone is modified to some extent by admixture with particles from other groups.

Briggs and McLane,[2] using the method of least squares, have established a quantitative relationship between the mechanical composition and the moisture equivalent, based on data covering 104 types of soil. The resulting probable error of the coefficients in the relationship established is 1.7 per cent.[3] In attempting the correlation of the mechanical composition with the wilting coefficient the same relative values for the sand, silt, and clay coefficients that were obtained by Briggs and McLane in their moisture-equivalent correlation have been used in our computations. The actual values of the coefficients

[1] Briggs, L. J., Martin, O. F., and Pearce, J. R. The Centrifugal Method of Mechanical Soil Analysis. Bulletin 24, Bureau of Soils, U. S. Dept. of Agriculture, 1904, p. 33.

[2] Briggs, L. J., and McLane, J. W. The Moisture Equivalent of Soils. Bulletin 45, Bureau of Soils, U. S. Dept. of Agriculture, 1907, p. 18.

[3] This value should not be confused with the probable error of a single determination, as given by Briggs and McLane.

were adjusted to give the best calculated values for the wilting coefficient, but the same proportion among the coefficients was maintained. The formula used is as follows:

$$0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay} = \text{wilting coefficient.}$$

In this formula the "sands" refer to the percentage of particles ranging from 2 to 0.05 millimeter in diameter, the "silt" to particles from 0.05 to 0.005 millimeter in diameter, and the "clay" to particles smaller than 0.005 millimeter in diameter. Table XXII [1] gives the mechanical composition of each of the soil types, the computed value of the wilting coefficient as determined by the above formula, the observed value of the wilting coefficient, and the residuals or differences between the observed and the computed values.

TABLE XXII.—*Comparison of the observed wilting coefficient with that found by computation from the mechanical analysis.*

Soil.	Types of soil.	Coarse sand.	Fine sand.	Silt.	Clay.	Coefficient.		Residuals.	Ratio of observed to computed.
						Computed.	Observed.		
		Per ct.	*Per ct.*	*Per ct.*	*Per ct.*				
7	Coarse sand	60.4	37.1	0.8	1.6	1.8	0.9	+0.9	0.50
2	Fine sand	28.2	64.4	4.7	3.9	3.1	2.6	+ .5	.84
8	do	35.4	55.1	4.8	4.5	3.6	3.3	+ .3	.92
9	do	29.9	56.7	5.0	8.2	3.8	3.6	+ .2	.95
3	Sandy loam	33.1	50.0	8.6	7.5	4.9	4.8	+ .1	.98
4	Fine sandy loam	2.8	59.8	30.2	6.9	10.3	9.7	+ .7	.94
12	Loam	3.4	55.5	21.8	19.1	9.5	10.3	− .8	1.08
A	Sandy loam	32.4	28.8	26.7	11.8	9.9	9.9	.0	1.00
B	Fine sandy loam	15.8	42.4	28.7	12.9	10.7	10.8	− .1	1.01
C	do	19.2	35.6	30.6	14.7	11.4	11.6	− .2	1.02
5	Loam	2.0	48.8	37.7	12.3	13.5	13.9	− .4	1.03
D	do	3.6	35.2	41.4	14.4	14.6	15.2	− .6	1.04
14	Clay loam	5.1	27.0	35.2	32.5	14.5	16.2	−1.7	1.12
E	do	3.2	43.7	45.1	17.1	16.0	16.5	− .5	1.03
6	do	4.4	20.5	52.6	22.0	16.6	16.3	+ .3	.98

The ratio of the observed to the computed value of the wilting coefficient is given in the last column of the table in order to provide a basis of comparison as regards accuracy with the other physical measurements. The mean ratio [2] is 1, with a probable error of ± 0.025. This large probable error is due mainly to soil No. 1, which has a departure no greater than some of the other soils but which on account of its very small wilting coefficient gives a ratio which is widely divergent from the rest of the series. The formula for computing the wilting coefficient, when affected with the probable error, then becomes:

$$\frac{0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay}}{1 \pm 0.025} = \text{wilting coefficient.}$$

[1] The writers are indebted to the Bureau of Soils for the mechanical analyses. No mechanical analyses were available for samples Nos. 10 and 13.

[2] In determining the values of the sand, silt, and clay coefficients so as to give a mean ratio equal to unity, soil No. 1 was disregarded, since a better general agreement was obtained in this way. This is virtually what would have happened if the method of least squares had been applied to the experimental data. In all calculations of probable error, however, this soil has been included with the rest.

GRAPHICAL REPRESENTATION OF THE RELATIONSHIP BETWEEN THE WILTING COEFFICIENT AND THE PHYSICAL MEASUREMENTS OF MOISTURE RETENTIVITY.

The experimental results given in the preceding tables are shown graphically in figure 9. The wilting-coefficient determinations are plotted as abscissas, while the axis of ordinates is taken successively to represent the moisture equivalent, the hygroscopic coefficient, the

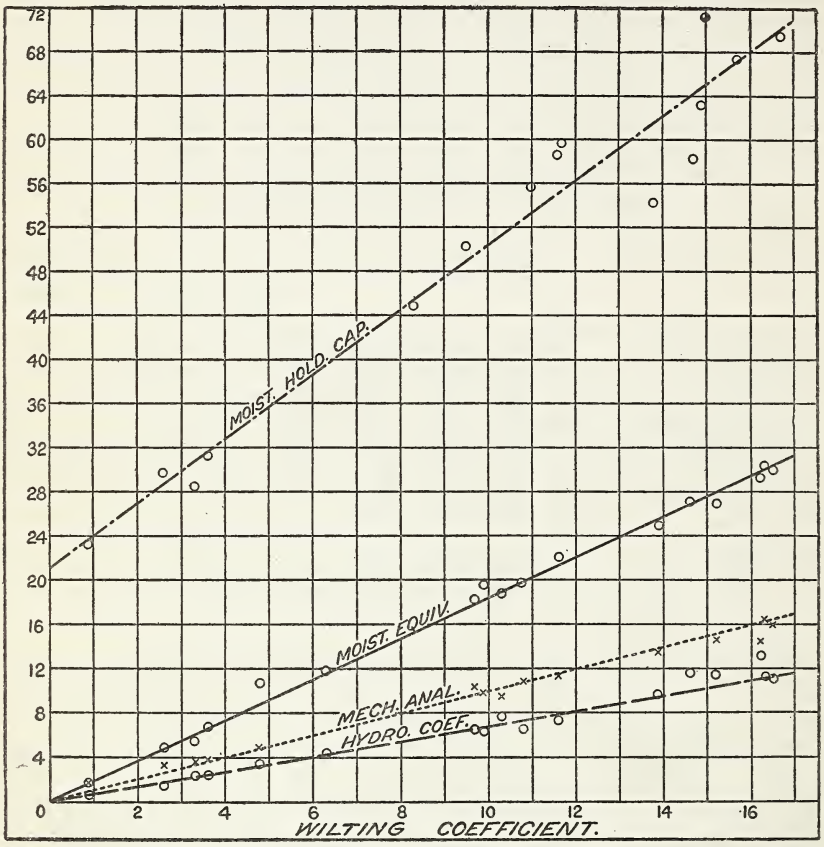

FIG. 9.—Chart showing the linear relationship between the wilting coefficient and physical measurements of the moisture retentiveness of soils. The wilting coefficient is represented by the axis of abscissas, while the axis of ordinates for the different graphs represents the moisture retentivity of the soil as measured by the hygroscopic coefficient, the moisture equivalent, and the moisture-holding capacity, and as computed from the mechanical analysis. The quantity employed as ordinate in each case is designated on the graph.

moisture-holding capacity, and the computed value of the wilting coefficient as determined from the mechanical analysis. The resulting graphs are designated by their respective ordinates. The slope of the graph in each case corresponds to the ratio used in the equation.

COMPARISON OF THE ACCURACY OF INDIRECT PHYSICAL METHODS FOR DETERMINING THE WILTING COEFFICIENT.

Since the numerical value of the ratio used in calculating the wilting coefficient by indirect methods varies considerably according to the method employed, it is necessary for purposes of comparison to express the probable error in each case as a percentage of the ratio which it affects. This comparison is given in the following table:

TABLE XXIII.—*Comparative accuracy of the ratios in the indirect methods for determining the wilting coefficient.*

Methods.	Ratio.	Probable error of mean ratio.	
		Absolute value.	Per cent of ratio.
Moisture equivalent	1.84	±0.013	±0.7
Hygroscopic coefficient	.68	± .012	±1.8
Moisture-holding capacity	2.90	± .06	±2.1
Mechanical analysis	1.00	± .025	±2.5

The probable error of the mean ratio shows the degree of uncertainty that is attached to the value given for the ratio. That is to say, if the moisture-equivalent series were repeated, the chances are even that the mean ratio would fall between 1.827 and 1.853. In other words, in a soil having an observed moisture equivalent of 18.4 per cent the chances are even that in so far as the accuracy of the ratio is concerned the wilting coefficient lies between 9.93 and 10.07. This corresponds to an uncertainty of ±0.7 per cent in the value of the wilting coefficient calculated by means of the ratio 1.84, as shown in the last column of the table, in which the probable error of the mean ratio is given, expressed as a percentage of the ratio itself. This affords at once a means of comparing the accuracy of the different methods. It will be seen that the probable error in calculating the wilting coefficient by the moisture-equivalent method is about 0.7 per cent; by the hygroscopic-coefficient method 1.8 per cent, or over twice as great; by the moisture-holding capacity method over 2.1 per cent, or three times as great; and by the mechanical-analysis method 2.5 per cent, or nearly four times as great.

It should be clearly recognized that the formulas which have been deduced will not necessarily give the correct calculated value of the wilting coefficient within the limits of the probable error of the ratio. The uncertainty regarding the value of the observed quantity (moisture equivalent, hygroscopic coefficient, etc.) enters into the calculation of the wilting coefficient for any particular soil, in addition to the uncertainty of the ratio. According to the formulas a linear relation existed in each case and the observed departures are attrib-

uted to accidental experimental errors. If this is true, then the probable error of the calculated wilting coefficient for a given soil can be made to approach the probable error of the ratio as a limit simply by increasing the accuracy and number of the determinations of the observed quantity.

The probable error of a single determination of the wilting coefficient in our experiments is given below for each method, expressed as a percentage of the wilting coefficient:

	Per cent.
Moisture-equivalent method	± 2.9
Hygroscopic-coefficient method	± 7.1
Moisture-holding capacity method	± 8.3
Mechanical-analysis method	±10.0

These errors are not to be applied to any other determinations, since they represent simply the accuracy attained in our particular experiments. If the number of physical measurements made upon each soil had been increased, the error would have been reduced.

FORMULAS SHOWING RELATIONSHIPS BETWEEN PHYSIOLOGICAL AND PHYSICAL MEASUREMENTS OF MOISTURE RETENTIVITY.

For convenience in reference the formulas for determining the wilting coefficient in a given soil by indirect methods are here presented in collected form, together with the probable error.

$$\text{Wilting coefficient}=\frac{\text{moisture equivalent}}{1.84\ (1\pm0.007)}.$$

$$\text{Wilting coefficient}=\frac{\text{hygroscopic coefficient}}{0.68\ (1\pm0.018)}.$$

$$\text{Wilting coefficient}=\frac{\text{moisture-holding capacity}-21}{2.90\ (1\pm0.021)}.$$

$$\text{Wilting coefficient}=\frac{0.01\ \text{sands}+0.12\ \text{silt}+0.57\ \text{clay}}{1\pm0.025}.$$

SUBSIDIARY FORMULAS.

The subsidiary formulas which follow as the result of the interrelationships established are also here included. The probable error has been omitted, since its determination from the formulas would always include the experimental errors of the wilting coefficient determination, due to the fact that the physical measurements are not directly compared.

DETERMINATION OF THE MOISTURE EQUIVALENT.[1]

Moisture equivalent=wilting coefficient×1.84.
Moisture equivalent=hygroscopic coefficient×2.71.
Moisture equivalent=(moisture-holding capacity−21)×0.635.
Moisture equivalent=0.02 sand+0.22 silt+1.05 clay.

[1] These equations refer to moisture-equivalent determinations made with a centrifugal force equal to 1,000 g. (gravity) and should not be confused with the equation given by Briggs and McLane in which a force of 3,000 g. was employed.

DETERMINATION OF THE HYGROSCOPIC COEFFICIENT.

Hygroscopic coefficient=wilting coefficient×0.68.
Hygroscopic coefficient=moisture equivalent×0.37.
Hygroscopic coefficient=(moisture-holding capacity−21)×0.234.
Hygroscopic coefficient=0.007 sand+0.082 silt+0.39 clay.

DETERMINATION OF THE MOISTURE-HOLDING CAPACITY.

Moisture-holding capacity=(wilting coefficient×2.9)+21.
Moisture-holding capacity=(moisture equivalent×1.57)+21.
Moisture-holding capacity=(hygroscopic coefficient×4.26)+21.
Moisture-holding capacity=(0.03 sand+0.35 silt+1.65 clay)+21.

These formulas establish for the first time a relationship between the various physical and physiological measurements of moisture retentivity, and while the coefficients may be modified as the result of further investigation, it is believed that the equations will prove of practical value in the study of the relationship of the plant to soil moisture, both in the field and in the laboratory.

DETERMINATION OF THE MAXIMUM AVAILABLE MOISTURE.

The maximum available moisture in any soil is represented by the difference between the moisture-holding capacity and the wilting coefficient. It is therefore possible to express the maximum amount of available moisture that a soil is capable of holding in terms of the relationships given above. It should be recalled that the determinations of moisture-holding capacity, upon which the relationships are based, were made with a soil column 1 centimeter in height. The amount is therefore far in excess of that found in drained soils under field conditions. The relationships are expressed in the following formulas:

Maximum available moisture=(wilting coefficient×1.9)+21.
Maximum available moisture=moisture equivalent+21.
Maximum available moisture=(hygroscopic coefficient×2.8)+21.
Maximum available moisture=(0.02 sand+0.23 silt+1.08 clay)+21.
Maximum available moisture=(moisture-holding capacity×0.65)+7.

The formulas show that the difference in the maximum amount of available moisture that two soils are capable of holding is equal to the difference of their moisture equivalents; to 1.9 times the difference of their wilting coefficients; and to 2.8 times the difference of their hygroscopic coefficients.

SUMMARY.

The object of this investigation was to determine the extent of the variation exhibited by different plants with respect to the minimum point to which they can reduce the moisture content of the soil before permanent wilting occurs. It has heretofore been believed that

plants differ widely in this respect and that drought resistance is in part due to the additional supply of water which is available to some plants through the greater force which they exert upon the soil moisture. The results of this investigation have led us to conclude that the differences exhibited by plants in this respect are much less than have heretofore been supposed and are so small as to be of little practical utility from the standpoint of drought resistance. As compared with the great range in the wilting coefficient due to soil texture, the small differences arising from the use of different species of plants in determining the wilting coefficient become almost insignificant.

The moisture content of the soil corresponding to the wilting of the plant growing in a confined soil mass is usually spoken of as nonavailable moisture. It has been found that plants are capable of reducing the moisture content of the soil far below that corresponding to the wilting point, and that a steady loss of moisture goes on through the plant tissues even after the death of the plant. Therefore the moisture content at the wilting point can not all be considered as nonavailable, and the term wilting coefficient has been adopted to indicate the moisture content of the soil at the time of the permanent wilting of the plant.

The wilting coefficient is then defined as the moisture content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in the moisture content as a result of a deficiency in the soil-moisture supply. By a permanent reduction in the moisture content of the leaves is meant a condition from which they can not recover their turgor in an approximately saturated atmosphere without the addition of water to the soil. In the case of most plants wilting accompanies the reduction of the water content of the leaves and is the criterion used to determine the wilting coefficient of a soil for that plant. The definition as stated is applicable also to those plants which, owing to structural peculiarities, do not give visible evidence of a reduction of the moisture content of the leaves. The wilting coefficient for such plants is determined by means of the balancing method.

In making wilting-coefficient determinations the following precautions are necessary:

(1) The soil used should be as uniform as possible.

(2) The soil should be brought to a uniform water content before being used.

(3) All loss of water should be prevented except that due to the transpiration of the plant.

(4) All sudden fluctuations in temperature should be avoided.

(5) The moisture determination should be made as soon as the plant has first reached a wilted condition from which it can not recover when placed in a damp chamber.

The method employed consists in growing the plants in a small glass pot, evaporation from the soil surface being prevented by means of a seal of wax which is melted and flowed over the soil surface. In the case of monocotyledons this wax seal can be applied immediately after planting the seeds and the seedlings will grow readily through the wax, which forms a perfect seal around the stems. In the case of dicotyledons the wax, which is usually a mixture of paraffin and petrolatum having a low melting point and low heat conductivity, can be melted and flowed around the stems of the seedlings without injury. During growth the pots are kept immersed in a water bath to avoid condensation of the soil moisture on the pot walls.

When these precautions are observed, the probable error of the mean of the determinations from 12 pots does not usually exceed 1 part in 100, which is comparable with the accuracy with which the moisture retentiveness of the soil used can be determined by purely physical methods.

The wax-seal method is also particularly adapted to the study of transpiration, since all loss of water is avoided except that taking place through the plant.

Wilting-coefficient determinations have been made in a series of 20 soils ranging from sands to clays. In this work, involving about 1,300 determinations, a large number of varieties of the different crop plants have been tested, as well as many native plants from the Great Plains.

The results obtained show that species differ only slightly as regards the soil-moisture content at which permanent wilting first takes place. Taking 100 to represent the average wilting coefficient, the different species tested (except Colocasia and Isoetes) give an extreme range from 92 for Japan rice to 106 for a variety of corn. Most of the species and varieties tested differ much less than this. On the same scale the great crop plants gave the following values, obtained by combining the different varieties: Corn 103, wheat 99, oats 99, sorghum 98, millet 97, barley 97, rye (one variety only) 94, rice 94, grasses 97, and legumes 101.

The conclusion is thus reached that the differences exhibited by crop plants in their ability to reduce the moisture content of the soil before wilting occurs are so slight as to be without practical significance in the selection of crops for semiarid regions. Furthermore, it is believed that the slight differences which have been observed are largely due not to the ability of one variety to exert a greater

tractive force upon the soil moisture than another, but to the more perfect root distribution of one variety as compared with another. Drought resistance in certain plants can not, then, be attributed to their ability to exert a greater force upon the soil moisture and so gain an additional water supply.

A series of comparisons has also been made of the relative time of wilting of different plants grown together in the same pot. In practically every case wilting occurred simultaneously, which is in harmony with the above conclusions.

A balancing method has been developed for determining the wilting coefficient for plants in which wilting is difficult to observe owing to structural peculiarities. The plant is potted in a glazed pot and the soil surface sealed with wax, as before. The potted plant is then mounted horizontally in a frame balanced on knife-edges. The water transpired by the plant is at first replaced from the supply in the soil. During this time the soil end of the system tends to move upward, owing to the loss of water, and is kept balanced by adjusting a counterpoise. A short period then occurs during which the water lost through transpiration is supplied both from the soil and from the storage tissues of the plant. During this time the system appears sluggish. Finally the amount supplied from the soil is insufficient to offset the increasing amount lost from the storage tissues of the plant and the direction of motion of the system is reversed, the plant moving upward. The soil-moisture content at this time corresponds to the wilting coefficient of that soil for the particular plant used, since the loss of water from the plant tissues would be accompanied by wilting except for structural peculiarities.

It has been shown by this method that the olive and the cactus undergo a reduction in the moisture content of their aerial parts at the time other plants wilt, although no outward evidence of such loss is apparent.

That portion of the soil-moisture content which is available for plant growth is represented by the difference between the actual water content and the wilting coefficient. The latter determination is consequently essential in any critical study of the relation of plant growth to soil moisture. The desirability of a rapid determination of the wilting coefficient in connection with field work led to an investigation to determine whether the wilting coefficient could be computed from physical measurements of the moisture retentivity of the soil. A comparison of the wilting coefficient has been made with the moisture equivalent, hygroscopic coefficient, moisture-holding capacity, and the mechanical analyses of a series of soils ranging from sand to clay. From this comparison a series of linear relationships has been established, as expressed in the following

equations, which thus provide a means of computing the wilting coefficient when direct determinations are not feasible.

$$\text{Wilting coefficient}=\frac{\text{moisture equivalent}}{1.84\ (1\pm0.007)}.$$

$$\text{Wilting coefficient}=\frac{\text{hygroscopic coefficient}}{0.68\ (1\pm0.018)}.$$

$$\text{Wilting coefficient}=\frac{\text{moisture-holding capacity}-21}{2.90\ (1\pm0.021)}.$$

$$\text{Wilting coefficient}=\frac{0.01\ \text{sand}-0.12\ \text{silt}-0.57\ \text{clay}}{(1\pm0.025)}.$$

The second term of the quantity within the parentheses shows the probable error of the relationship in each case and constitutes a measure of the relative accuracy of the different methods.

The moisture-equivalent method, in which the measurements are made with the aid of the centrifugal machine exerting a force 1,000 times that of gravity, is the most accurate and satisfactory of the indirect methods.

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